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A COMPARISON OF TWO INERTIAL REFERENCE
PROFILOMETERS USED TO EVALUATE
AIRFIELD AND HIGHWAY PAVEMENTS

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DEDICATION

This thesis is dedicated to my grandmother, Mrs. Agnes Buldberg, *in celebration of her 80th year* of life, and to my parents, Mr. and Mrs. Henry Doepke for their continual support and encouragement.

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A COMPARISON OF TWO INERTIAL REFERENCE
PROFILOMETERS USED TO EVALUATE
AIRFIELD AND HIGHWAY PAVEMENTS

by

Chris Edward Doepke, B. C. E.

THESIS

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May 1976

PREFACE

This study is the result of a suggestion from Mr. L. M. Womack of the United States Air Force Weapons Laboratory (AFWL) and was supported by both the AFWL and the Center for Highway Research at The University of Texas at Austin. Entitled "A Comparison of Two Inertial Reference Profilometers Used to Evaluate Airfield and Highway Pavements," it examines the comparability of two similar pavement profile measuring systems owned by the United States Air Force and The Texas State Department of Highways and Public Transportation.

This project was initiated from personal encouragement from Drs. W. Ronald Hudson and B. Frank McCullough of The University of Texas at Austin and Mr. L. M. Womack. The author gratefully acknowledges their invaluable contributions of guidance and assistance throughout the course of this study. The author's appreciation is also extended to Drs. Thomas W. Kennedy and Hugh J. Williamson for reviewing this manuscript and adding helpful suggestions. Special thanks are extended to Mr. Leon Snider for engineering consultations; Mr. Randy Wallin for programming support; Messrs. Snider, Wallin, and James Long for making the profilometer measurements; Master Sergeant Donald Hartmann and the other personnel at Bergstrom Air Force Base for their cooperation and assistance during the runway measurements; and to Mrs. Marie Fisher and Mrs. Patricia Henninger for their patient and excellent administrative advice and support.

The contents of this study reflect the views of the author, who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the United States Air Force.

Chris Edward Doepke

January 1976

ABSTRACT

This thesis documents a comparison of two similar pavement profile measuring systems owned by the United States Air Force and the State Department of Highways and Public Transportation. The comparison includes descriptions of the systems, a copy of the computer program used to interpret the systems' outputs, plotted profiles from each system for visual comparison and all data used in the statistical analysis. Measurements for the comparison were taken on asphalt concrete airfield and highway pavements and on a portland cement concrete runway. Limitations in the comparison experiment restricted conclusions drawn to that of basic comparability for rigid pavements. Definite conclusions could not be drawn concerning flexible pavements. Recommendations include possible mechanical and operational improvements to the systems, and extension or improvement of the comparison.

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CHAPTER 1. INTRODUCTION

In the past decade, considerable effort has been expended to develop pavement evaluation-performance systems. A major innovation has been the application of the "serviceability-performance concept" (Ref 1) to the evaluation of highway pavements and the accompanying use of relatively high speed profiling devices to predict serviceability ratings. Much work has been done to develop this concept as it applies to highway pavements; however, there has been relatively less application of such concepts to the more complex realm of airfield pavement performance.

Paramount to the effective application of any systems approach to pavement management is the establishment of decision criteria with which one can evaluate the system's output (Ref 2). In other words, it must be decided what constitutes failure of the pavement system. There are two concepts that may be used to solve this problem. One is to define failure as the inability of a pavement to fulfill its purpose, that is, being functional. Functional failure is inherent in the serviceability-performance concept, where empirically determined terminal levels of serviceability are used to define functional failure for highway pavements. Since some determination of pave-serviceability is necessary to define functional failure, this concept of defining failure has not been applied to airfield pavements, a major factor being that certain aircraft types can safely operate on pavements that have "failed" for others.

The second concept of defining failure is to quantify the various mechanisms and manifestations of failure, or distress (i.e. fracture, distortion, and disintegration). There are, however, no precise or generally accepted definitions of this type of failure that relate to some level of serviceability or performance (Ref 2). Structural adequacy and surface condition ratings have been used for years in attempting to evaluate pavement structures. They, however, offer little help in actually defining degree of failure (Ref 3), providing only estimates of how bad a pavement is and when and how much maintenance or repair is necessary.

As concern grows for the improved safety, comfort, and convenience of air travel, the ever increasing costs of constructing and maintaining the investment represented by our airfield pavements necessitates continual progress in developing effective and efficient airfield pavement evaluation-performance concepts and methods.

Background

The pavement serviceability-performance concept is a direct result of the American Association of State Highway Officials (AASHO) Road Test conducted in the late 1950's and early 1960's. An essential element of a systems approach to highway pavement design, the serviceability-performance concept is, in concise terms, the application of subjective serviceability ratings to define a "wear out" or performance function for a particular pavement.

Carey and Irick (Ref 1) define present serviceability as "the ability of a specific section of pavement to serve...traffic in its existing condition," and "performance is assumed to be an overall appraisal of the serviceability history of a pavement." The application of these terms to define a wear out function in a systems approach to airfield pavement design was developed by Hudson and Kennedy (Ref 3) and is shown in Fig 1.1. McCullough and Pearson (Ref 4) outlined some of the difficulties in applying the highway pavement design system to U.S. Air Force airfield pavements. The determination of airfield pavement serviceability is more difficult than in the highway pavement case because of widely varying aircraft (vehicle) weights, landing gear configurations, speeds, and the seemingly more critical fact that the vehicle must safely leave and return to the pavement surface.

The lack of progress in applying the serviceability concept to airfield pavements is not the result of a lack of research concerning airfield pavements. The National Aeronautics and Space Administration (NASA), the U.S. Air Force, and others have long been investigating the operating problems related to airfield pavement roughness (Ref 5). Of particular interest were the efforts of the U.S. Air Force Weapons Laboratory (AFWL), and their accompanying use of profilometers to obtain runway profiles.

The AFWL, in cooperation with the Federal Aviation Administration, is in the midst of a program to quantify runway roughness. To do so, two types

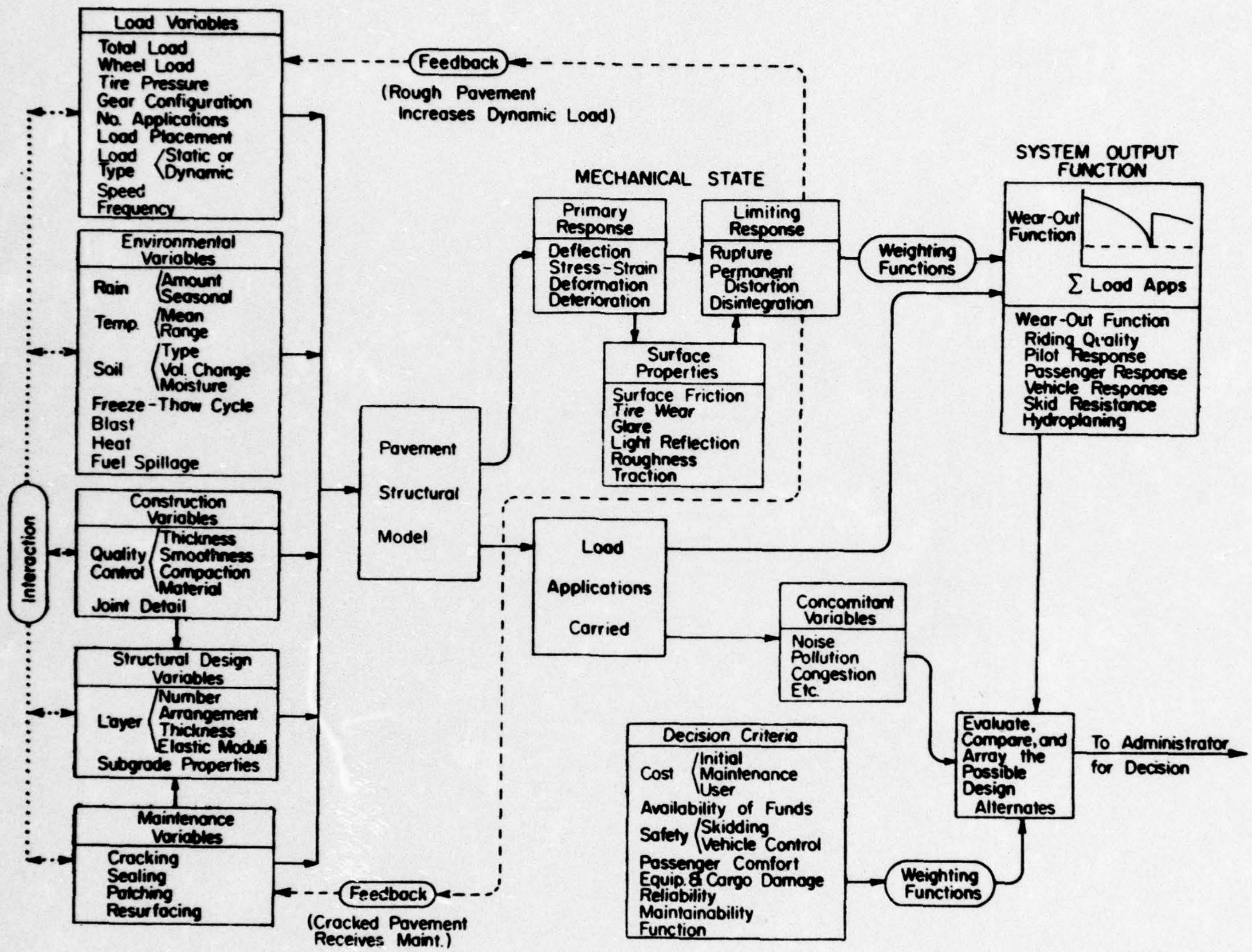


Fig 1.1. Block diagram of the airfield pavement system (Ref 3).

of runway profiling systems were developed to obtain input profiles for a computerized aircraft response simulation model. The first is a laser system (Fig 1.2) and obtains profile data by referencing a leveled laser beam. The second system is an inertial type system, and obtains data by referencing an inertial platform. The Air Force's inertial type system - hereafter termed Air Force Profilometer - was designed for airfield pavements and is conceptually similar to the Surface Dynamics Profilometer (trade name for the General Motors Road Profilometer) used by the Center for Highway Research at The University of Texas at Austin in conjunction with the State Department of Highways and Public Transportation. With the encouragement and assistance of the AFWL, the task of comparing the Air Force Profilometer and the Surface Dynamics Profilometer was undertaken. Thus, in April, 1975, the Air Force Profilometer was brought to Austin, Texas, and replicate measurements were made with both profilometers on the flexible and rigid (asphaltic and portland cement concrete) runways at Bergstrom Air Force Base, a flexible section of highway pavement, and a rigid pavement bridge deck.

Concurrent with the efforts to compare the two profilometers, it was believed some attempt could be made to develop a preliminary model to predict serviceability ratings for airfield pavements using Surface Dynamics Profilometer measurements and pilot serviceability ratings of the runways at Dallas' Love Field (Ref 6). Assuming such serviceability indices would be at, or approaching, a terminal level (the new Dallas-Fort Worth Regional Airport was already under construction at the time of data acquisition), a limited verification of the model would be possible if profiles were available from an airport that would produce relatively high serviceability ratings. Fortunately, profile data of the Dallas-Fort Worth Regional Airport (D/FW) were going to be available from the AFWL, and since the runways had been servicing traffic for less than two years, a smoother profile and thus higher ratings could be expected. The use of different profiling systems to obtain profile data on the Love Field and D/FW runways was recognized as a restriction, but perhaps anticipating some correlation between the Air Force and Surface Dynamics Profilometers, it was believed corrections could be made to achieve valid results.

There were, however, complications. Because of equipment malfunctions and a rigid schedule, profile data from the Air Force's inertial system were not available. However, profile data on one runway as measured with the Air

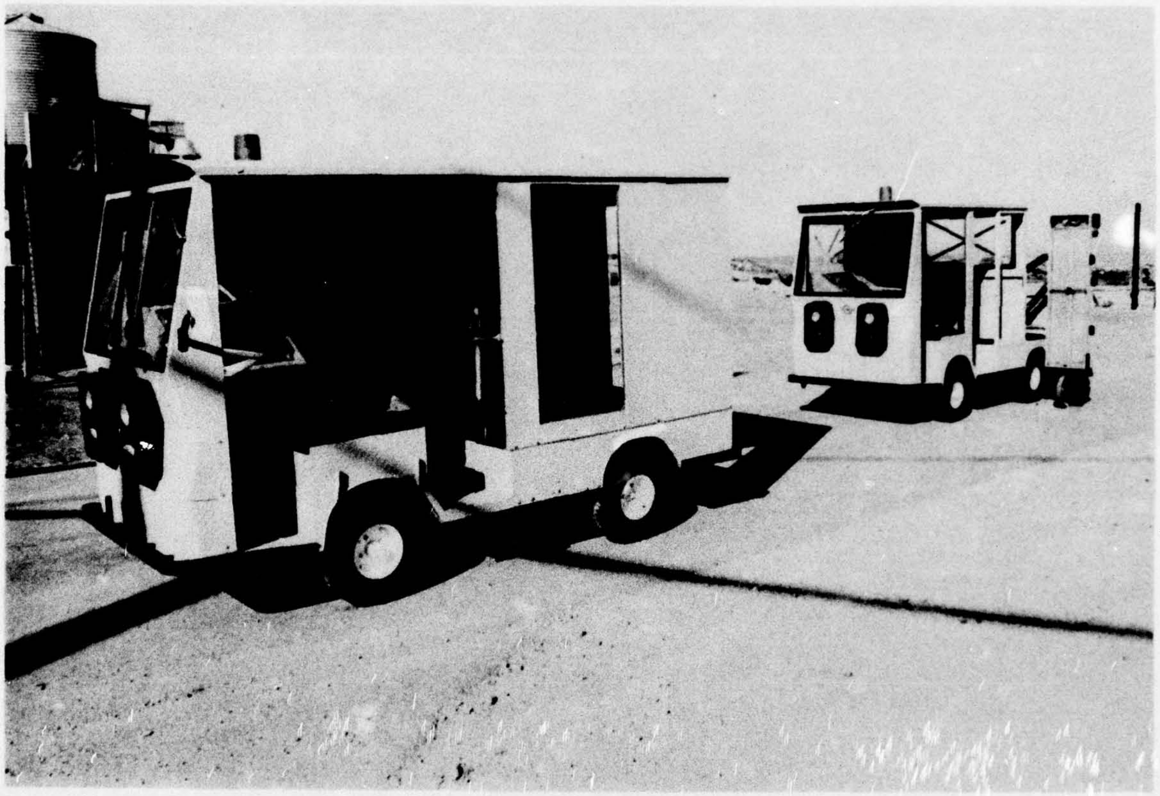


Fig 1.2. U.S. Air Force laser profilometer system (photo courtesy of USAF Weapons Laboratory).

Force laser system were made available, and in actuality are more accurate data, as they represent a true profile (Ref 7). As a result, the comparison of the two inertial type profilometers to validate the results of predicting airfield serviceability ratings was no longer necessary. The comparison was continued, however, in order to evaluate the profilometers in applications other than called for in their original designs.

Another complication, which concerned the development of the preliminary airfield serviceability index model, made it impossible to obtain the necessary profile data within the time frame of this study. Thus, without such profile data in digital form, a planned regression analysis of profile data upon pilot serviceability ratings was not performed, and, hence, the discussion of the application of the serviceability-performance concept to airfield pavements in Appendix 4 is investigative in nature and in proposal form.

Objectives

This study documents a comparison of the Air Force and Surface Dynamics Profilometers, discussing basic similarities and differences of the systems and their outputs. The purpose of this comparison is to evaluate each profilometer with respect to the other and in regard to present applications of each system. A secondary purpose of this study is to investigate the application of the serviceability-performance concept to airfield pavements, providing another application for each profilometer.

Scope

The comparison of profilometers is based primarily on the output of the systems, with background information given concerning the basic characteristics of each system. It does not delve into a complex component by component evaluation. Chapter 2 documents the basic characteristics of the Air Force Profilometer as well as some of the fundamental concepts of inertial reference profilometers, and Chapter 3 presents similar information for the Surface Dynamics Profilometer. Chapter 4 discusses the experiment designed to compare the output of the profilometers as determined by a modified version of a computer program used to characterize highway profiles. It also briefly guides the reader through a visual comparison of plotted profiles. Finally,

Chapter 4 discusses a statistical analysis of the comparison of mean roughness amplitudes as determined by each profilometer.

The summary and conclusions of the comparison are given in Chapter 5. The computer program used to characterize each profilometer's output is listed in Appendix 1. Appendix 2 is a collection of plotted profiles from each system presented for visual comparison, and Appendix 3 contains the mean roughness amplitude data used in the statistical analysis of Chapter 4. Appendix 4 discusses an investigation of the applicability of the serviceability-performance concept to airfield pavements, essentially proposing a model to predict airfield serviceability indices.

CHAPTER 2. AIR FORCE INERTIAL PROFILOMETER SYSTEM

As stated previously, the Air Force Weapons Laboratory (AFWL) operates two profilometer systems to obtain data for their investigations into airfield pavement roughness. The system used for this study, the inertial type, is based on the same principle of inertial reference on which the Surface Dynamics Profilometer is based.

General Description

The Air Force Profilometer system (Fig 2.1) was developed for the AFWL by Dynasciences Corporation, Scientific Systems Division, Blue Bell, Pennsylvania. The system was designed to be accurate to 0.1 inch (0.254 centimeter) in measuring and recording the vertical profile of a runway within the 3 to 400-foot (0.9 to 121.9-meter) wavelength region (Ref 8). The measured profile is recorded in digital form in 6-inch (15.24-centimeter) increments in a format compatible with a CDC 6600 computer. The Air Force Profilometer requires three operators: a driver, a speed controller, and a technician. was originally equipped with a laser guidance system to minimize the transverse error in following a 10,000-foot (3048-meter) survey line to less than six (6) inches (15.24 centimeters). It was later discovered that because of joints and paint stripes on the runway, an experienced driver could easily follow the survey line within the required tolerances (Ref 7). Thus, except where no such reference lines exist, the laser guidance system is not used in normal operation.

Principle of Operation

The basic principle of using an inertial reference, rather than an absolute reference as in rod and level measurements, is based upon a simple mechanical vibrometer as illustrated in Fig 2.2. When the surface following wheel of the vibrometer encounters various surface irregularities, it is displaced vertically a distance, w, from an imaginary inertial reference. If

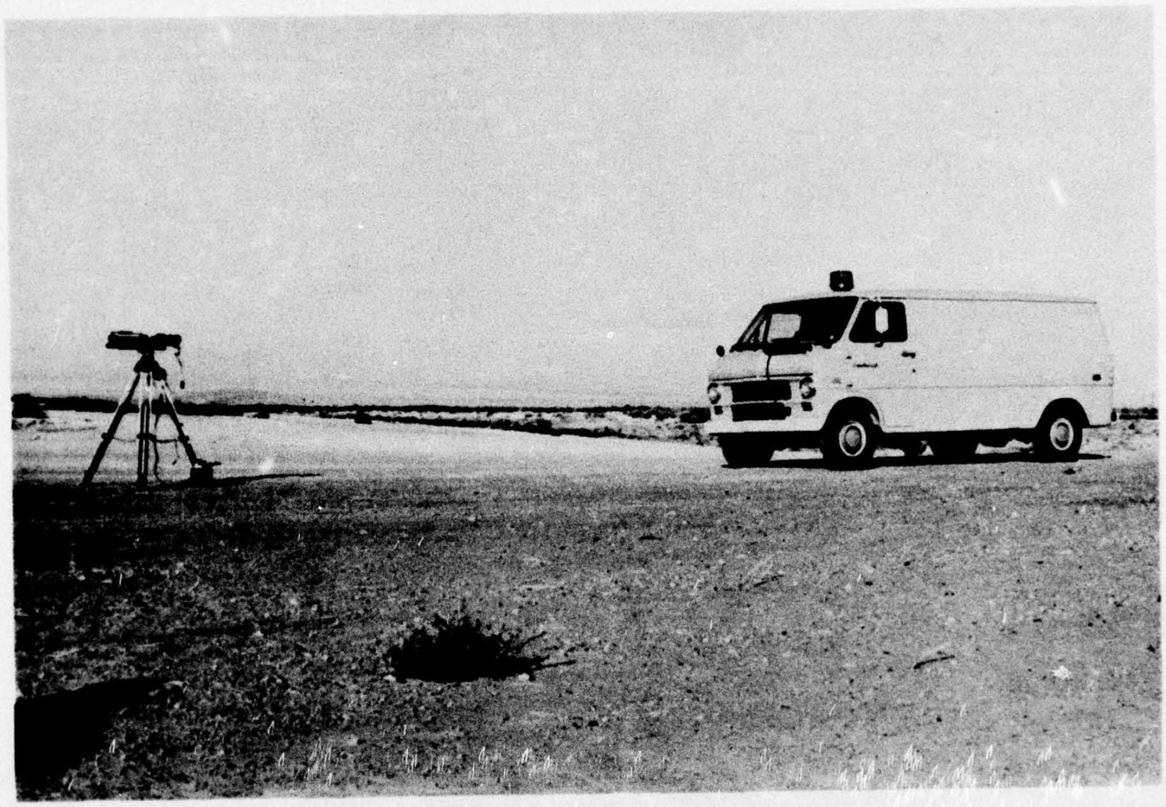


Fig 2.1. U.S. Air Force inertial profilometer (photo courtesy of USAF Weapons Laboratory).

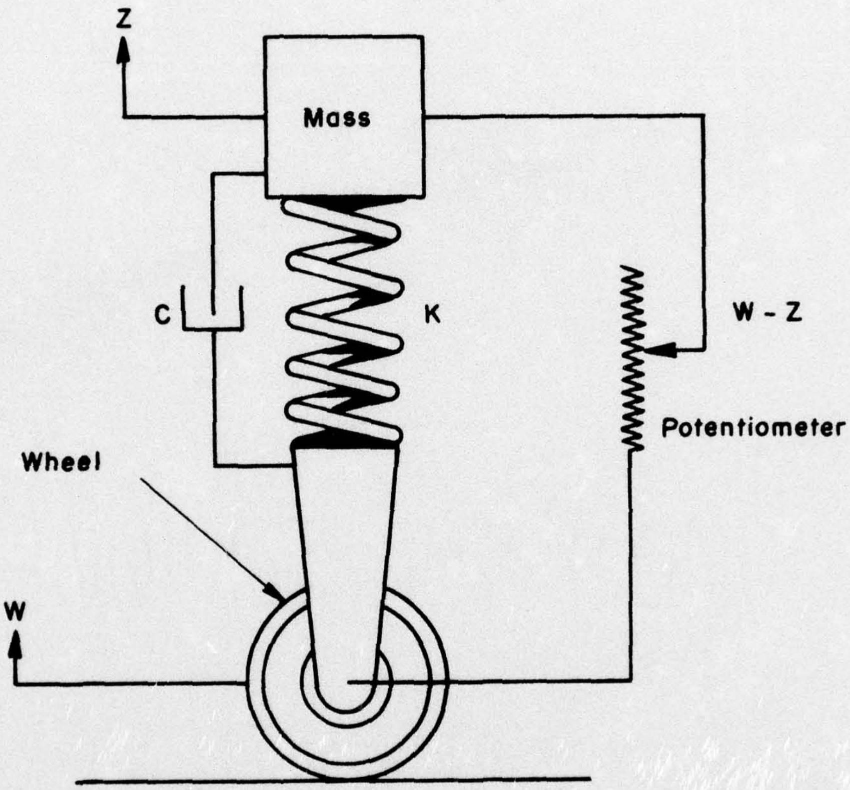


Fig 2.2. Mechanical vibrometer (Ref 9).

the vertical displacement (amplitude) is sufficiently large and the frequency of such displacements sufficiently high, the mass will be displaced vertically a distance z . The surface profile, with respect to the inertial reference, can then be obtained by adding the displacement of the mass (z) to the displacement of the following wheel with respect to the mass (w-z).

The wheel to mass displacement (w-z) is easily measured. The Air Force Profilometer uses a linear voltage differential transformer (LVDT), and the Surface Dynamics Profilometer a potentiometer, to provide a signal proportional to the displacement between the surface contour and the mass. To obtain the displacement of the mass (z), both the Surface Dynamics and the Air Force Profilometers perform two integrations of the acceleration of the mass ($\ddot{z}$) as measured by an accelerometer mounted on the mass. The pavement surface profiles are obtained by continuous solution of the following general equations:

$$w = (w-z) + \iint \ddot{z} \, dt \, dt \qquad \text{(Surface Dynamics)} \qquad (2.1)$$

$$w = \int \left[\frac{d}{dt} (w - z) + \int \ddot{z} \, dt \right] \qquad \text{(Air Force)} \qquad (2.2)$$

The continuous solution of Eq. 2.2 is sampled, digitized, and recorded every 6 inches (15.24 centimeters) by the Air Force Profilometer system.

Configuration of the Measurement System

The Air Force Profilometer is equipped with one contour following wheel as illustrated in Figs 2.3 and 2.4. The accelerometer which measures acceleration of the mass (the survey vehicle) is mounted on a stabilized "gimballed platform" mounted on the floor of the vehicle (Figs 2.3 and 2.5). The purpose of the stabilized platform is to provide a vertical axis for accelerometer input. Within an analog processor (see Fig 2.6), the accelerometer signal is integrated once and added to the first derivative of the following wheel position signal. This sum represents the inertially referenced rate of change of the surface profile.

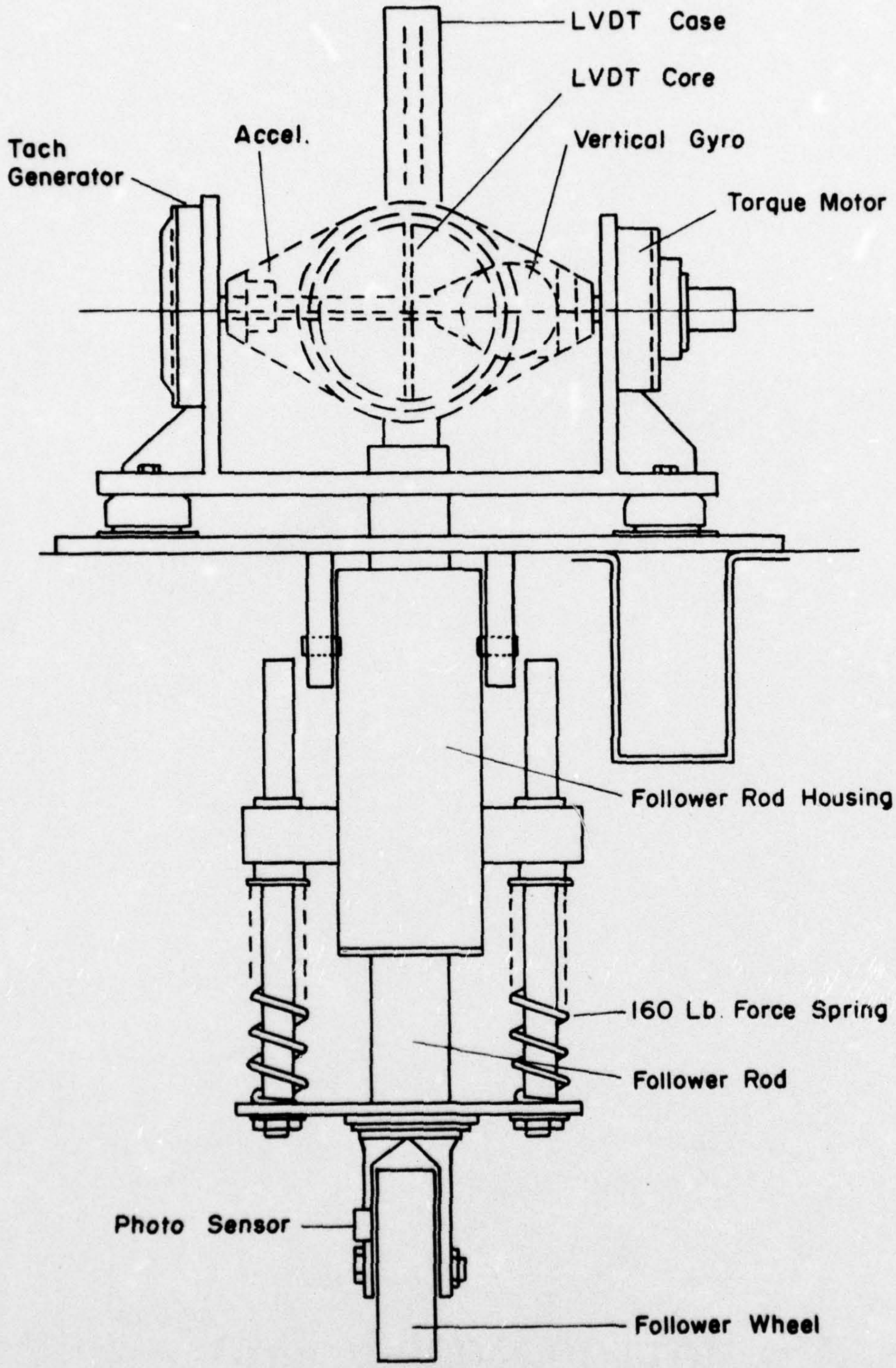


Fig 2.3. Air Force Profilometer following wheel assembly (Ref 8).

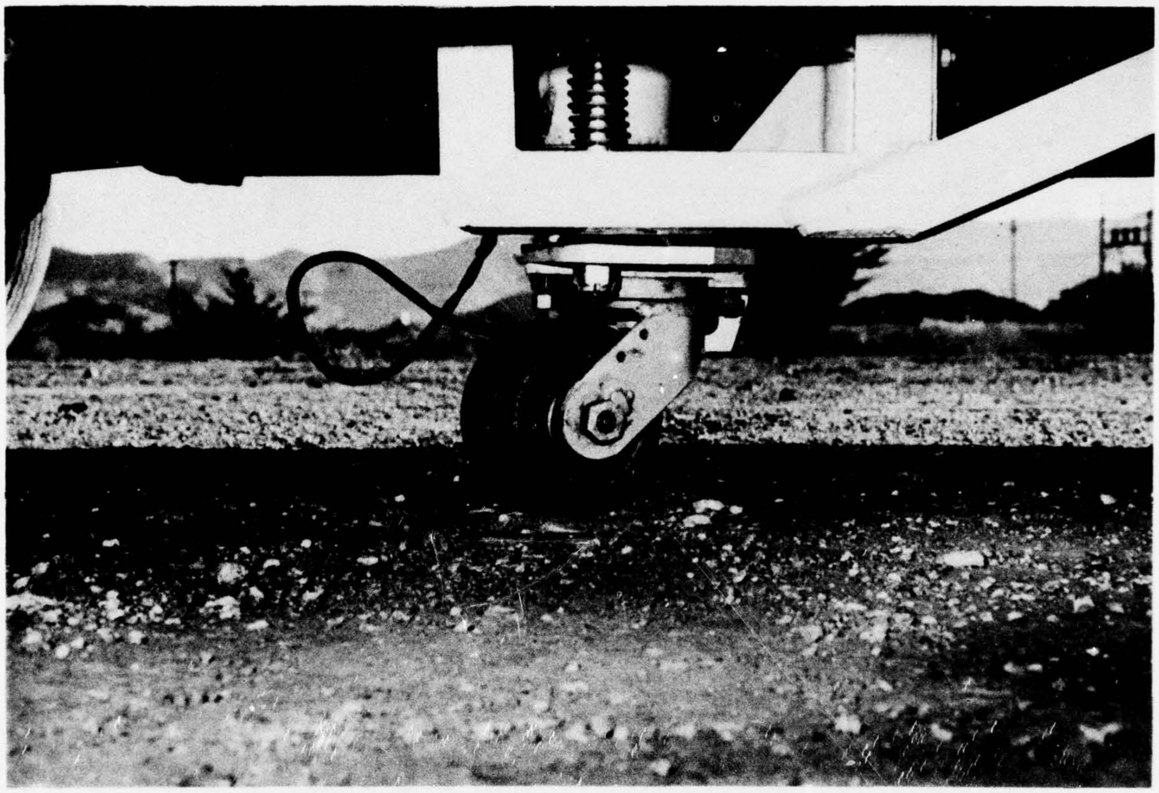


Fig 2.4. Air Force Profilometer following wheel (photo courtesy of USAF Weapons Laboratory).

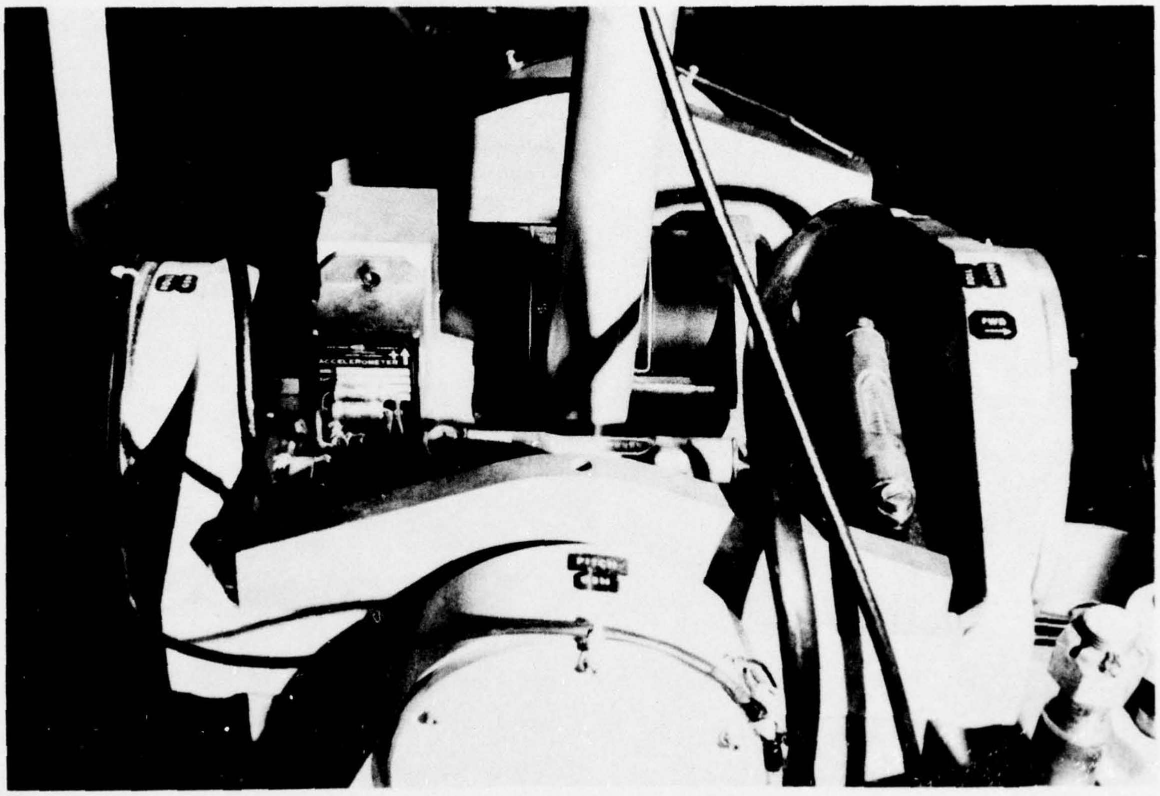


Fig 2.5. Air Force Profilometer stabilized platform (photo courtesy of USAF Weapons Laboratory).

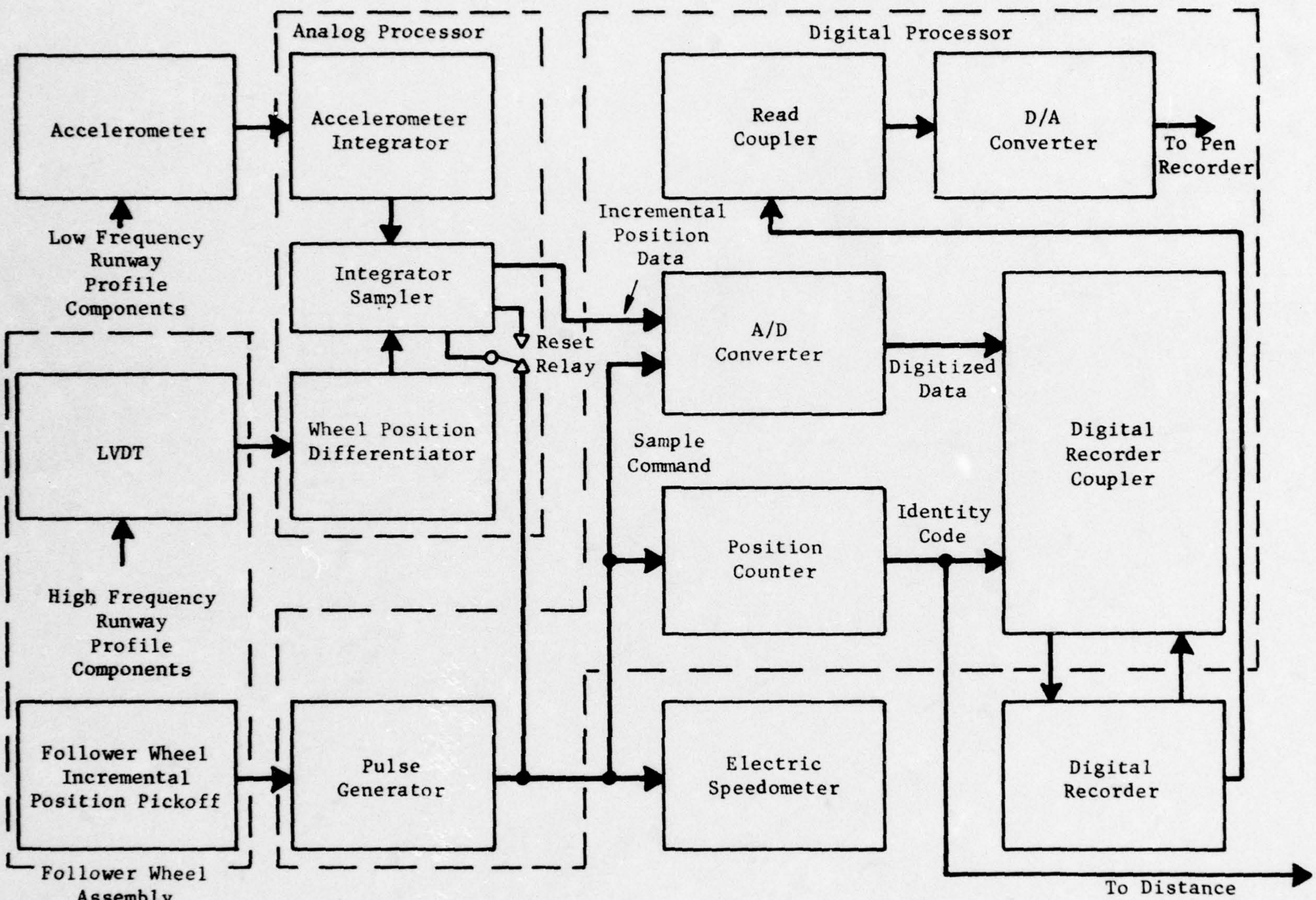


Fig 2.6. Block diagram of Air Force Profilometer measurement system (Ref 7).

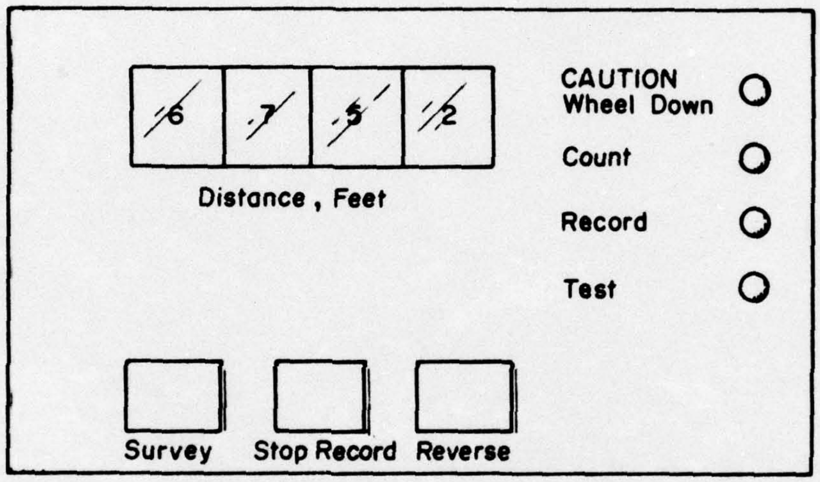
This rate of change, or velocity, is integrated by the "Integrator and Sampler" portion of the analog processor, with the integrator being reset every six inches. This output represents profile change per sample period and is referred to as the "Incremental Position" signal. The pulse for sampling every six inches (15.24 centimeters) is obtained from a photocell pickup of white marks every six inches (15.24 centimeters) along the 18-inch (45.72-centimeter) circumference of the following wheel. The Incremental Position is digitized in the Analog-to-Digital (A/D) converter portion of the digital processor, combined with a position identifier, multiplexed, and buffered prior to being recorded on the digital tape recorder, (Ref 8).

Other circuitry exists to read the recorded data, demultiplex it, and convert the data back to analog signals (D/A) for visual display on a strip chart or pen recording. The remaining subsystems shown in the block diagram are the speed control system and the control panel. The speed control system consists of an electric speedometer which receives its input from the photocell pickup and pulse generator used to sample the data. The speed controller uses a hand control of the vehicle accelerator to keep the electric speedometer within the proper range. The position counter provides the signal for the distance reading on the control panel (Fig 2.7).

Operating Procedures

Originally designed to be operated using a laser for steering guidance, the instruction manual (Ref 8) gives specific step-by-step procedures for measuring a runway profile with the Air Force Profilometer using the laser guidance system. Since the laser guidance system is not normally used, there remain two methods of obtaining pavement profiles. The first method is to achieve the proper measuring speed of 30 feet per second (9.14 meters per second) and then initiate the recording of data when the following wheel crosses the start of the survey line. The second method is to position the following wheel a set distance before the beginning of the survey line, record data during the acceleration of the profilometer, and later discard the data recorded prior to the desired survey line. Both of these methods were used in the course of this study.

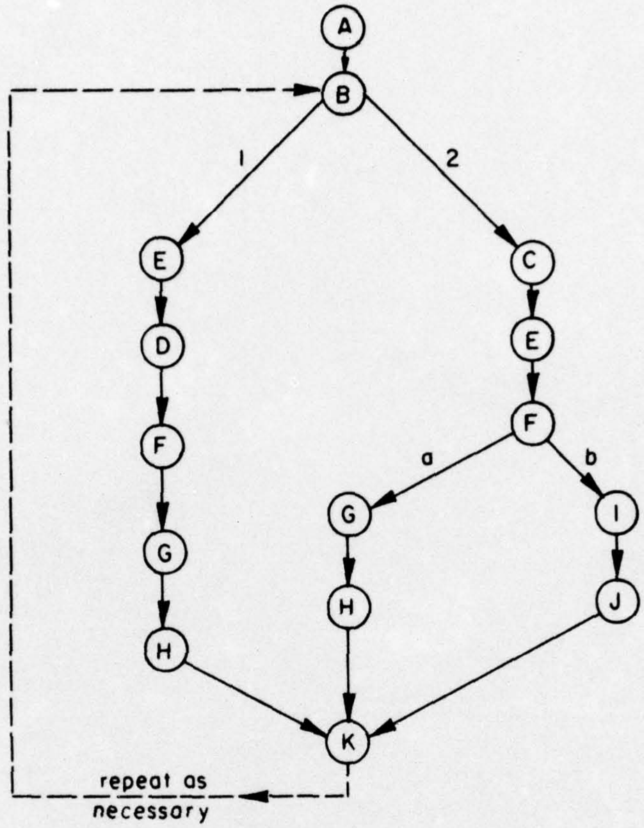
Figure 2.8 is the flow chart of the procedures followed to measure the profile of a given survey track. Assuming exclusive use of a runway,



Note : "Stop Record" and "Reverse" buttons used only with laser guidance system.

1 foot = .3048 meters.

Fig 2.7. Air Force Profilometer control panel.



Activities

A Warm up electronic components

B Position/level platform/lower wheel/check

C Technician depresses "survey" button (Fig 2.7)

D Technician depresses "survey" button at start of survey track

E Driver accelerates profilometer
Speed controller assumes control

F Driver follows survey track

G Technician releases "survey" button at end of survey track

H Driver stops profilometer after end of survey track

I Driver stops profilometer after end of survey track and moves profilometer forward until following wheel is at a reference point

J "Survey" button released

K Raise following wheel

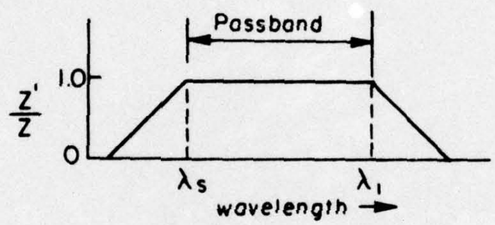
Note: Data are obtained whenever there is following wheel rotation and the "survey" button is depressed.

Fig 2.8. Flow chart of Air Force Profilometer operating procedures.

approximately ten minutes are required for each measurement of a 10,000-foot (3048-meter) survey track - approximately four minutes for preparation and six minutes to drive the length of the track.

Limitations and Possible Sources of Error

The basic limitation of the Air Force Profilometer, or of any inertial reference profilometer, is the lack of accurate reproduction of amplitudes throughout the entire frequency spectrum. This is best illustrated by the following Bode plot, where the ordinate is the ratio of measured to actual



amplitude and the abscissa is either wavelength or frequency. The above Bode plot would indicate that measured amplitudes are attenuated at wavelengths shorter than λ_s or longer than λ_1, leaving a band of wavelengths, or frequencies, where amplitude is accurately reproduced or "passed" by the system. This band is generally referred to as a passband, and for the design of the Air Force Profilometer was specified to be between 3 and 400-foot (0.9 to 121.9-meter) wavelengths.

The inaccuracies of a system in reproducing waveforms outside of the passband are a result of the individual frequency responses of the system components, i.e., accelerometer, LVDT, potentiometer, etc., and of the characteristics of the vehicle in which the system is contained. Other errors can be generated by the electronics used to handle and store the data and by the rate at which the data are digitized or sampled. In the graphical form of Bode plots, the system frequency response (transfer function) may be considered as the combination of a series of individual subsystem functions, as illustrated in Fig 2.9.

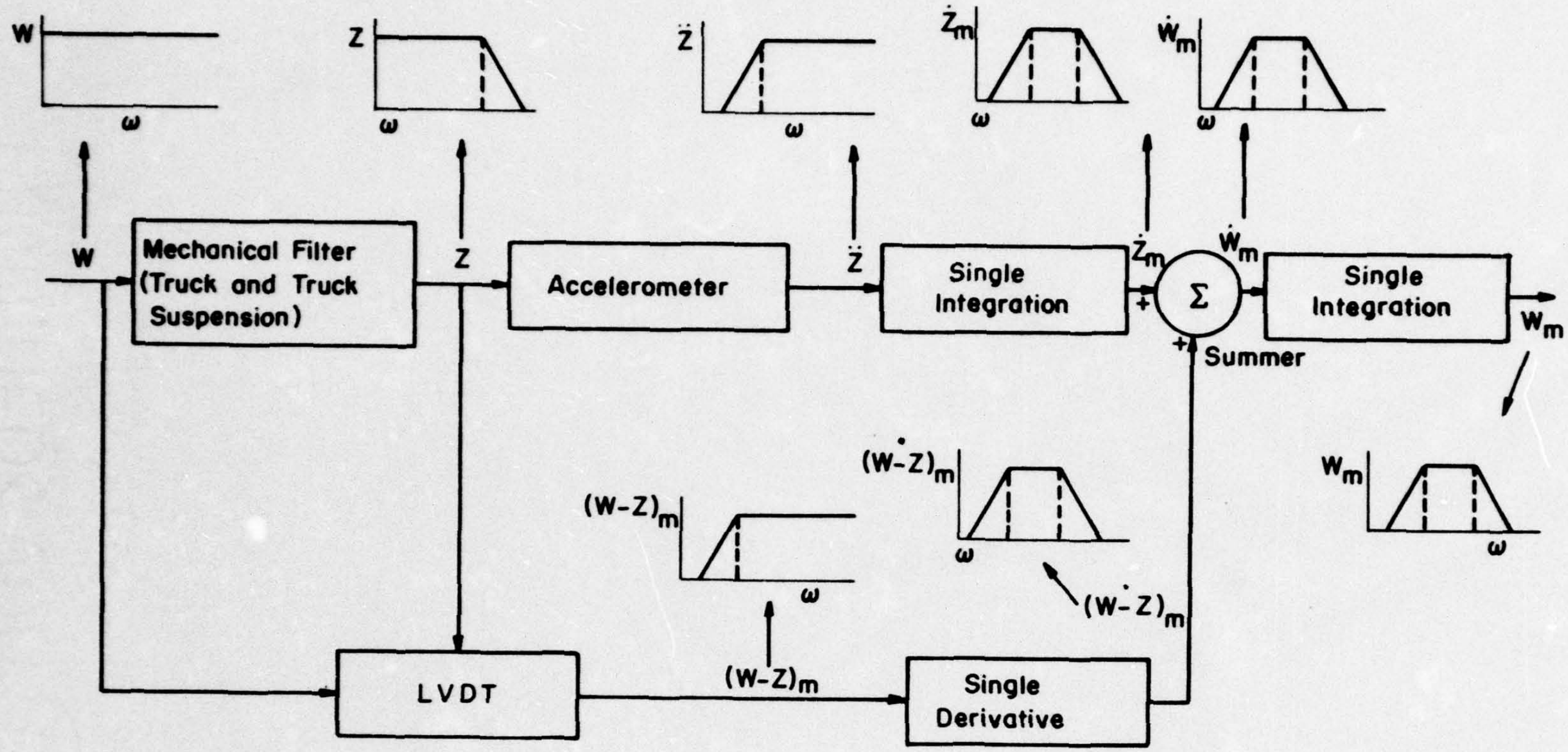


Fig 2.9. Conceptualized Air Force Profilometer system frequency response.

High-Frequency Response

The high-frequency (short wavelength) response of the Air Force Profilometer is primarily limited by the response of the LVDT, the size of the surface following wheel, the digitization rate, and the electronic handling of the data.

Linear Voltage Differential Transformer. The LVDT used in the Air Force Profilometer is a Schaevitz Engineering Model 5000 HRDC-2, with a range of ±5 inches (12.7 centimeters) and a linearity of less than 0.25 percent of full range (Ref 8). As the principal device for determining the amplitude of the high-frequency information, the nonlinearity of the LVDT could cause an error of 0.25 percent of ten inches, or 0.025 inch (.0635 centimeter). This maximum error is well within the design accuracy of 0.1 inch (.254 centimeter). In addition, the typical frequency response of this type of unit is from one to two orders of magnitude better than required (Ref 7).

Surface Following Wheel. Two factors are present when possible error caused by the surface following wheel is considered - wheel out of roundness and wheel size. It is clearly evident that if the wheel is not round, amplitude errors will result. It should also be evident that the following wheel does not respond to those portions of a profile with a radius of curvature less than the wheel itself. The wheel, then, will not accurately measure amplitudes or wavelengths shorter than twice its diameter of 11.4 inches (28.96 centimeters), as illustrated in Fig 2.10.

Digitization Rate. The rate at which profile information is sampled also limits the high-frequency response of the system. For any given sampling rate, there is a maximum frequency which can be detected. This frequency is known as the Nyquist frequency f_n and is defined as $1/2\Delta$ where Δ is the sampling interval in seconds (Ref 10). Thus, for the Air Force Profilometer sampling interval of 6 inches (15.24 centimeters) at 30 feet per second (9.14 meters per second), the interval is .01667 second, the Nyquist frequency of 30 Hertz (Hz) is three times as large as the 10 Hz frequency corresponding to the 3-foot (0.9-meter) wavelengths desired. Conversely, the maximum sampling interval allowed to detect 3-foot (.91-meter) wavelengths is 18 inches (45.72 centimeters). As a result, there should be no significant problem in properly defining the profile.

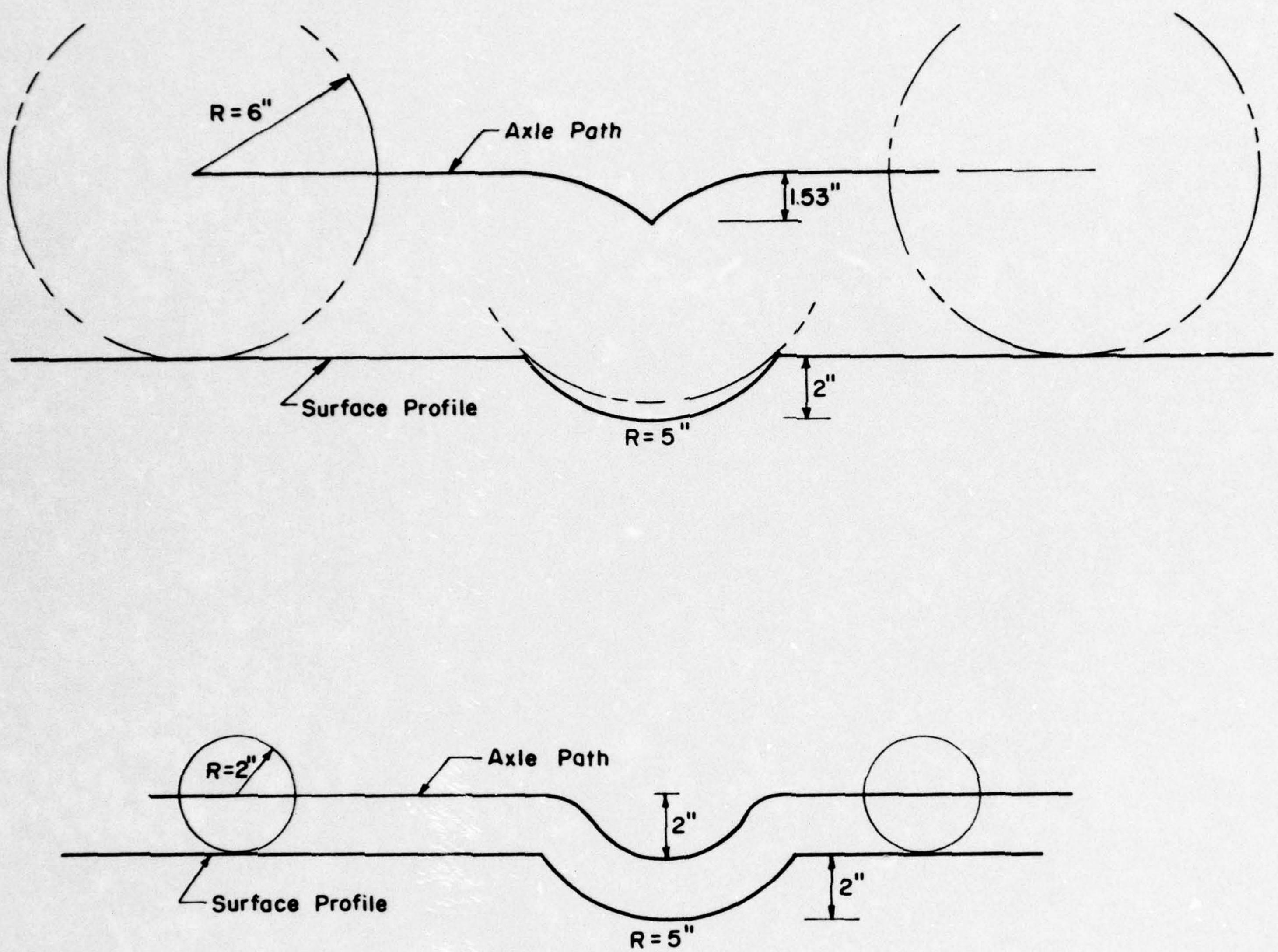


Fig 2.10. Effect of following wheel size.

Another possible source of error emanates from the device used to produce the sampling pulse. The Air Force Profilometer's digitizing pulse is generated by means of a photocell sensing white marks spaced 6 inches (15.24 centimeters) apart along the following wheel circumerence. This method should be more accurate than that used in the Surface Dynamics Profilometer, where the pulse generator is attached to the output shaft of the vehicle transmission, and therefore is dependent on the vehicle differential tire pressure, and temperature wear. Errors of this type, however, are normally insignificant.

Electronic Handling of the Data. The last primary limitation of high-frequency response is a result of the handling of the LVDT signal by the electronic components of the system. Reference 7 reports that as a result of the data from the LVDT being differentiated and then added to the singly integrated accelerometer signal, the high-frequency components of the LVDT signal are significantly amplified at frequencies greater than 9.78 Hz. However, as 10 Hz is the upper limit of the desired passband, filtering conducted during later analysis of the data eliminates the amplified portion of the signal, thus making this limitation irrelevant.

Low-Frequency Response

As illustrated in Fig 2.6, the low-frequency (long wavelength) components of a profile are measured by the accelerometer. The low-frequency response of the Air Force Profilometer is thus limited by the accelerometer, the stabilized platform it is mounted on, and the electronic components that handle the accelerometer signal.

Accelerometer. The accelerometer used in the Air Force Profilometer is a Systron-Donner, Model 4310A-1-CM, which has the following specifications:

Range: ± 1 g
Natural Frequency: 134 Hz
Nonlinearity: $<$ 0.05 percent of full range
Resolution: $<$ 0.001 percent of full range
Hysteresis: $<$ 0.02 percent of full range
Damping ratio: 0.769

The response of the accelerometer is adequate at the high end of the frequency passband; it is capable of responding to frequencies in excess of 25 Hz (Ref 7). This fact, however, has less significance, because the vehicle

suspension system acts as a more severe filter, transmitting frequencies to the accelerometer in the order of only 2 to 3 Hz (Ref 11). The low-frequency response of the accelerometer poses more of a problem. Reference 7 calculates the best and worst case maximum usable wavelengths as 900 and 100 feet (274.32 and 30.48 meters), respectively. In normal operation, the low-frequency passband limit lies somewhere between the aforementioned limits.

Stabilized Platform. A second source of low-frequency response error is caused by the accelerometer axis deviating from the vertical. A servo-leveled platform is provided to keep the axis aligned vertically. However, measured reaction times of the platform to changes in vehicle alignment varied from 10 to 20 seconds (Ref 7). As these times overlay the period of the maximum wavelength ($\approx$ 10 seconds), significant errors could result dependent on the rate of change of the vehicle alignment. Hence, the rougher the pavement, the greater the accelerometer tilt error.

Electronic Components. The high-frequency limitations of the electronic components that handle the data were briefly discussed earlier in this chapter. Although no similar low-frequency limitations were specifically cited in the references used by this writer, Ref 7 indicates the presence of low-frequency drift in the Air Force Profilometer system. Electronic component drift and noise were cited in an evaluation of the Surface Dynamics Profilometer (Ref 9) as possible sources of error. It is reasonable to assume similar conditions exist in the Air Force Profilometer electronic components. It should be noted, however, that vehicle heating and air conditioning systems should effectively reduce thermal drift errors.

Observed Accuracy and Operational Characteristics

In order to verify the accuracy of the Air Force Profilometer the AFWL compared profile data for a 400-foot (121.92-meter) test section as measured by rod and level, their laser system, and the inertial reference system. The resulting profiles are shown in Fig 2.11, where the end points have been normalized, or rotated to zero elevation. Because of the limited frequency response of the inertial reference type profilometer, all data were digitally filtered for a passband of 3 to 400 feet (.9 to 121.9 meters). The resulting plots of the test section filtered profiles for laser data and inertial data are shown in Figs 2.12 and 2.13, respectively.

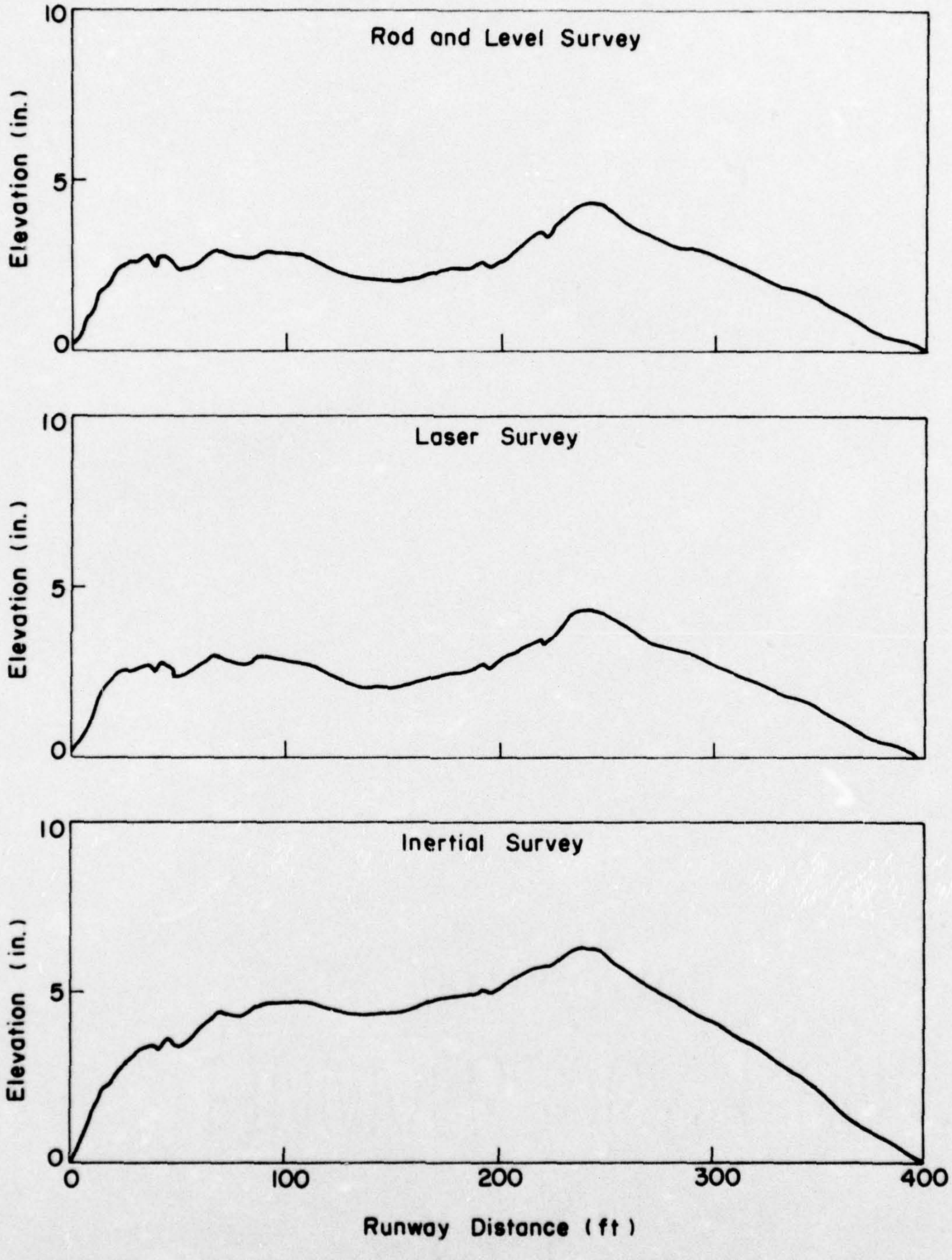


Fig 2.11. Air Force test section raw profiles (Ref 7).

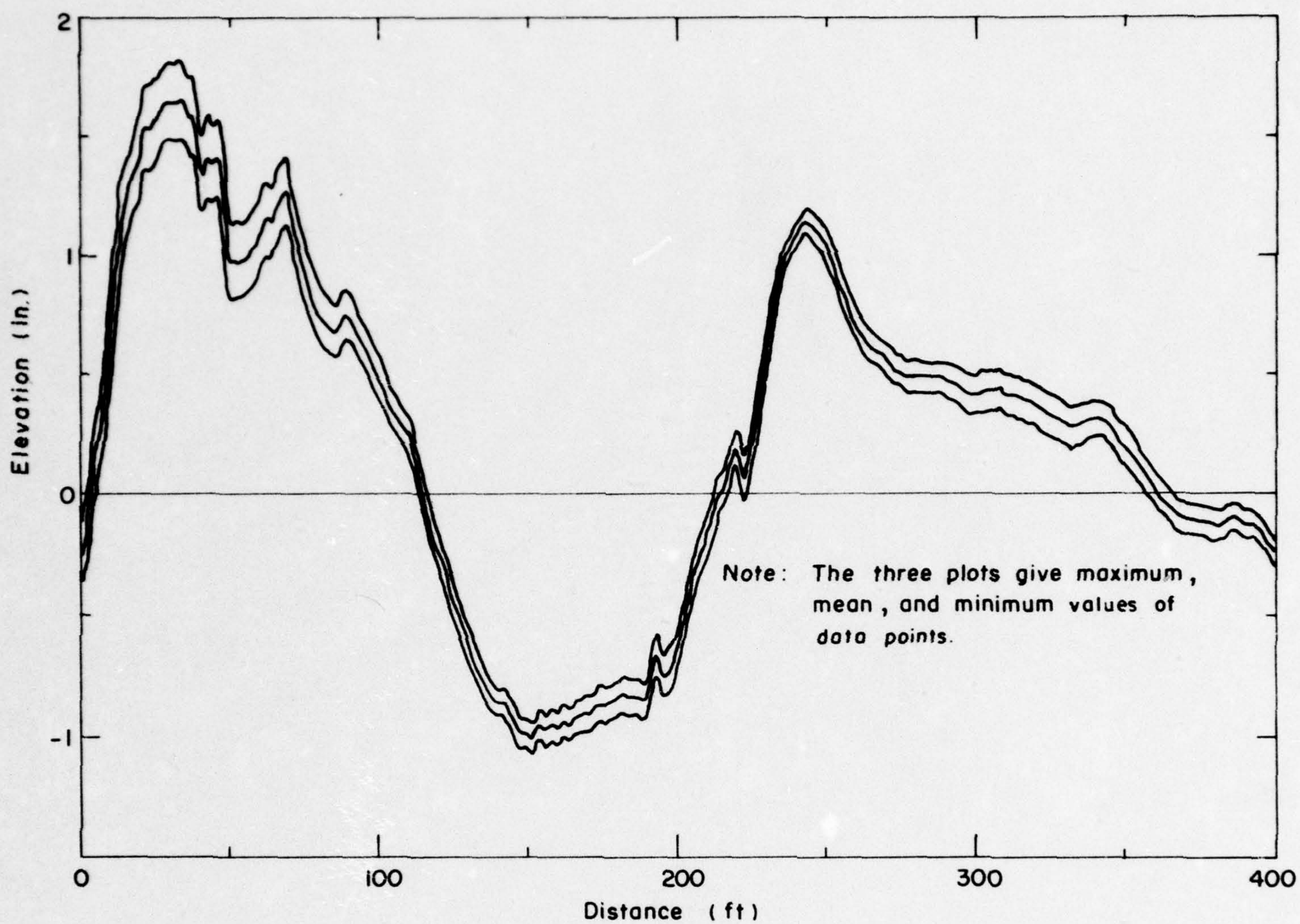


Fig 2.12. Deviation of Air Force laser profilometer data (Ref 7).

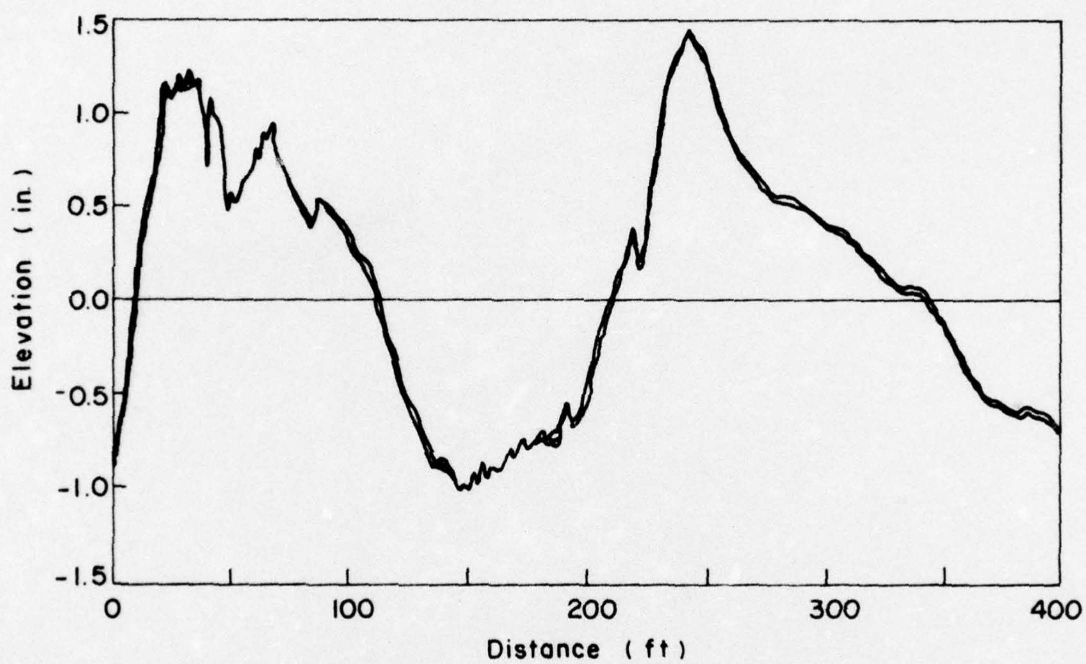


Fig 2.13. Deviation of filtered Air Force inertial profilometer data (Ref 7).

Figures 2.12 and 2.13 also illustrate the repeatability of both AFWL systems. Reference 7 determined the standard deviation of any given run with the inertial profilometer to be 0.14 inch (0.35 centimeter). This value was obtained by adding the individual variances of inertial profilometer (0.0072 inch or .0183 centimeter) and rod and level data (0.0114 inch or .0290 centimeter) to determine the variance of any given repetition. This indicates that the accuracy of the Air Force Profilometer, at least for the 400-foot (121.92-meter) test section, is very close (0.14 versus 0.10 inch or .36 centimeter versus .25 centimeter) to the specified accuracy, and that the repeatability of the profilometer is also very good. Another observation made in Ref 7 is that, for airfield pavements, vertical accelerations measured by the accelerometer are much less than 0.1 g, hence reducing the magnitude of expected accelerometer error by a factor of 10. Such a reduction adjusts the worst case maximum wavelength measurable by the system to 310 feet (94.49 meters) instead of 100 feet (30.40 meters), which is more consistant with the observed system inaccuracy.

As a relatively high speed profiling device, the Air Force Profilometer is an excellent device for obtaining pavement profile data. Its operation is relatively uncomplicated, involving three operators: a driver, a speed controller, and someone to operate the electronics and adjust the inertial table and following wheel. Such separation of responsibilities allows each operator to concentrate on only one function. Direct digital output saves the efforts and time of converting analog data to digital data at a different time and place. Ease of operation could, however, be improved by automating the following wheel positioning mechanism. Other observations are noted in Chapter 5, Summary, Conclusions, and Recommendations.

CHAPTER 3. SURFACE DYNAMICS PROFILOMETER SYSTEM

The Surface Dynamics Profilometer is a self-contained measuring device developed by the General Motors (GM) Research Laboratory in Warren, Michigan, and manufactured under license from GM by K. J. Law Engineers, Inc., Detroit, Michigan. The Surface Dynamics Profilometer has been described numerous times in various references (6, 9, 12, 13, 14, 15, 16). This chapter, therefore provides information in an abbreviated form to facilitate comparison with the Air Force Profilometer.

General Description

The Surface Dynamics Profilometer (Fig 3.1) is self-contained in a panel truck, which can be driven or transported to any paved surface for operation. The particular Surface Dynamics Profilometer used in this study has been utilized by The University of Texas at Austin since early 1968 as a highway research tool (Ref 15). Several changes and improvements have been made since then, but they have not changed the basic principles of operation or the overall configuration.

The Surface Dynamics Profilometer was designed to provide continuous profiles of the two wheelpaths of hard-surfaced highway pavements. As such, there are two following wheels, each in line with the profilometer truck wheels. It is designed for operation at varying speeds, thus offering a variable frequency response, although, in its usual application for obtaining Serviceability Index (SI) values, it is operated exclusively at 20 mph (32.19 kilometer/hr). The continuous profiles are digitized at a separate facility, where the standard output is vertical profile measurements approximately every 2 inches (5.08 centimeters). The Surface Dynamics Profilometer requires only two operators - a driver and a technician. The driver is responsible for guidance and speed control, the technician for operation of the electronic components and recording the data.

Fig 3.1. Surface Dynamics Profilometer (Ref 14).

Principle of Operation

The principle of operation of the Surface Dynamics Profilometer is identical to that of the Air Force Profilometer. The differences in the systems are in the number of profiles measured (two wheelpaths versus one), the mechanical design of the following wheel systems, and the handling and recording of the data. These differences are expanded upon in the remainder of this chapter.

Configuration of the Measurement System

The Surface Dynamics Profilometer is equipped with two contour following wheels extending from arms beneath the vehicle body (Fig 3.1). Accelerometers are mounted to the vehicle body directly above each following wheel to measure the vertical acceleration of the vehicle mass. These accelerations are doubly integrated in the profile computer, as illustrated in Fig 3.2. The motion of each following wheel with respect to the mass (truck) is measured with a potentiometer instead of an LVDT. The following wheel position signals are added to the doubly integrated accelerometer signals in the space spectrum rather than in the velocity spectrum, as in the Air Force Profilometer. The profile computer also contains a high pass filter that eliminates the unwanted low-frequency wavelength components that are very prevalent in highway pavements due to numerous changes in grade.

The pulse generator, which is coupled to the vehicle transmission provides a distance pulse used in digitizing the data and for triggering the strip chart recorder. The photocell pickup is normally used to provide the signal to start recording data at the start of the section of interests and as a distance check of known reference points.

Operating Procedures

An updated operation and maintenance memorandum for the Surface Dynamics Profilometer (Ref 15) was recently compiled that contains specific step-by-step operating procedures. In general, the procedures followed are

(1) warm up electronic components,
(2) set up system components,
(3) lower following wheels,
(4) make test/calibration run,
(5) raise following wheels,

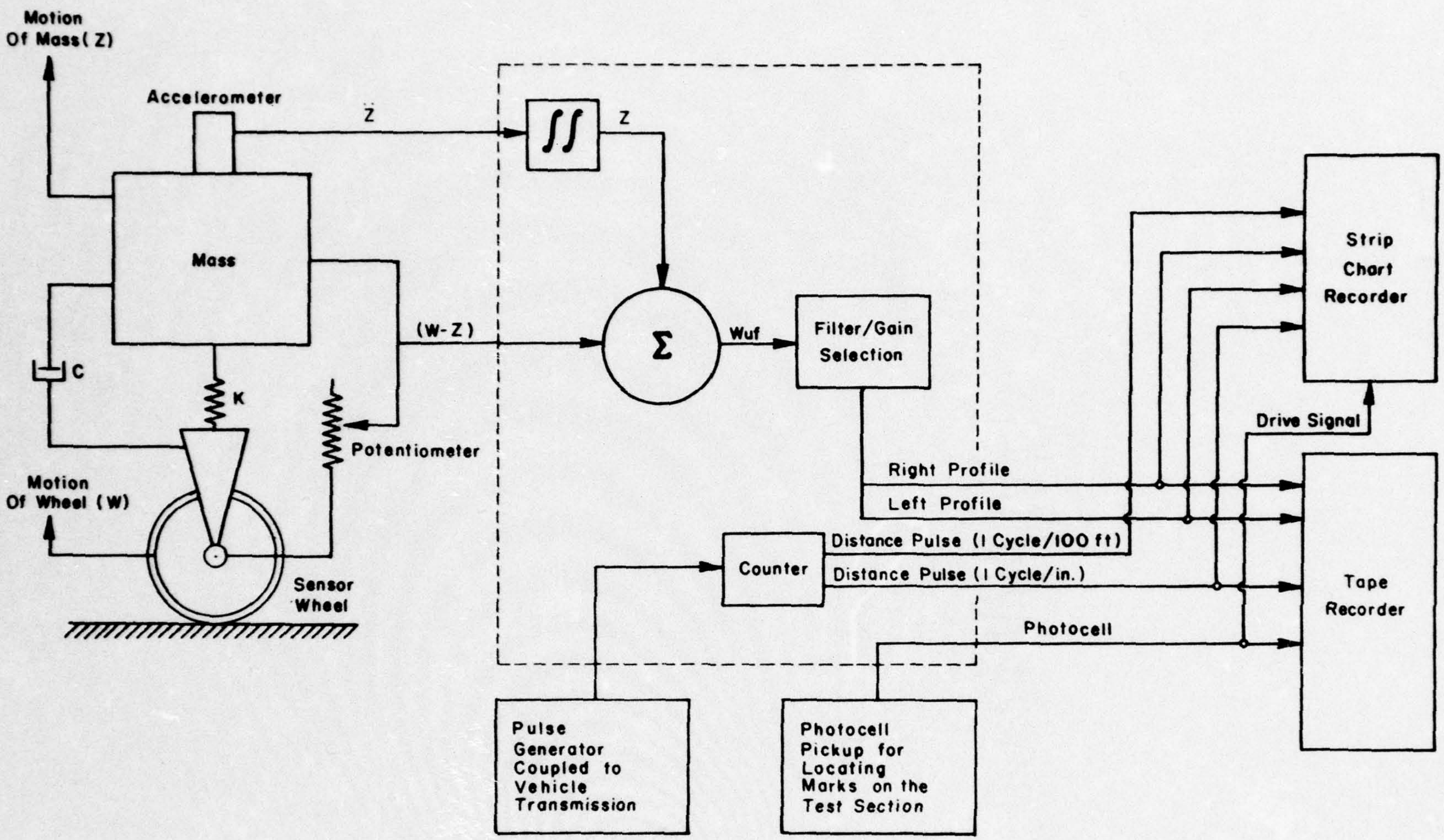


Fig 3.2. Block diagram of surface dynamics measurement system (Ref 14).

(6) return to start of section,
(7) record reference step size,
(8) accelerate to correct speed, letting photocell start recording of data at start of section,
(9) technician comments on voice track of tape recorder,
(10) stop tape recorder and strip chart at end of section,
(11) raise following wheels, and
(12) repeat as necessary.

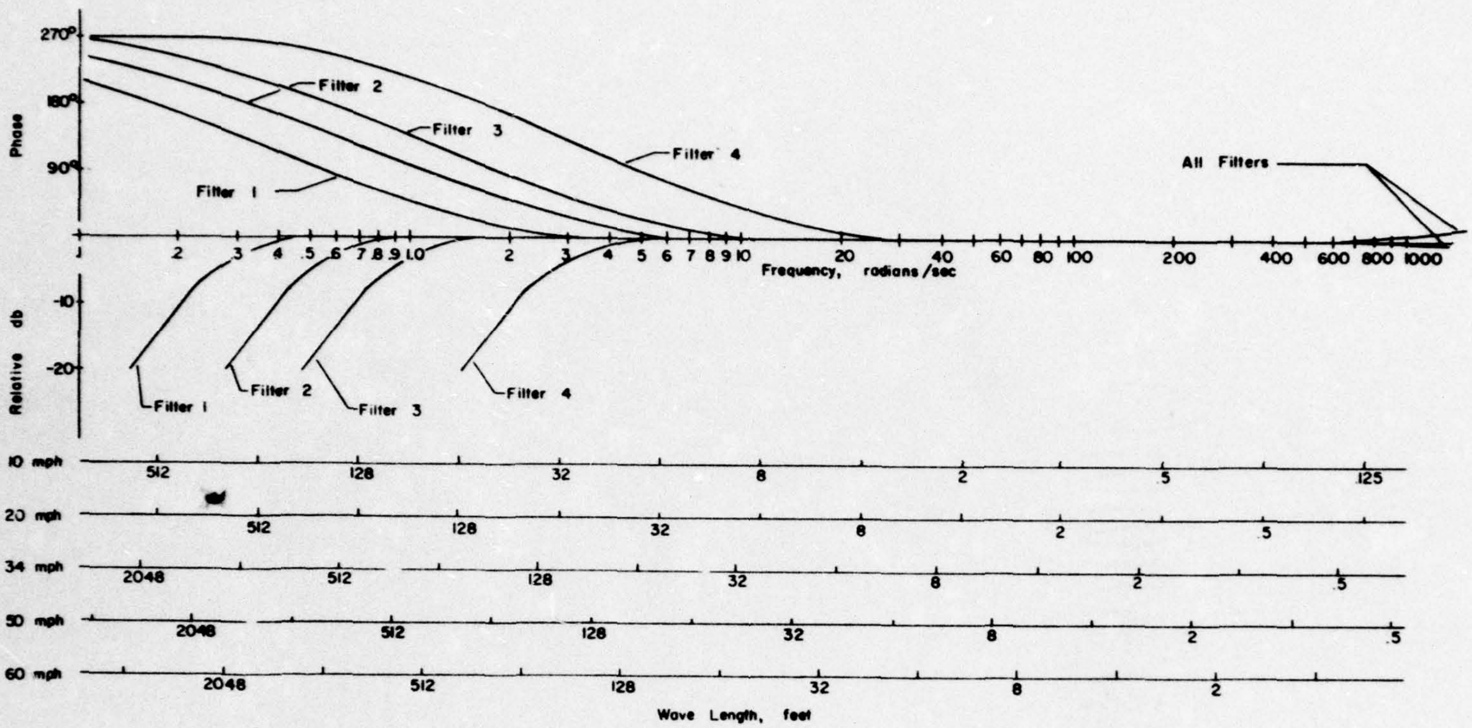
Limitations and Possible Sources of Error

The primary limitation of the Surface Dynamics Profilometer is its finite frequency response. The system frequency response for this system is illustrated in Fig 3.3, which shows, for any chosen operating speed, where profile phase shift and attenuation occur. The phase shift is a result of the highpass filtering process within the profile computer. Since the Air Force Profilometer does not filter its data, phase shift limitations are peculiar to the Surface Dynamics Profilometer. The system frequency response diagram effectively defines the pass bands for each operating speed. In a different form, Fig 3.4 graphically displays the effective passbands for various filter and speed combinations resulting in maximum phase shifts of 135 and 10 degrees. As previously discussed, a system's frequency response is comprised of a combination of its subsystem responses. Figure 3.5 illustrates the Surface Dynamic Profilometer subsystems responses and is comparable to Fig 2.9, which illustrates the same concept for the Air Force Profilometer. The system frequency response is divided into the high and low ranges for examination.

High-Frequency Response

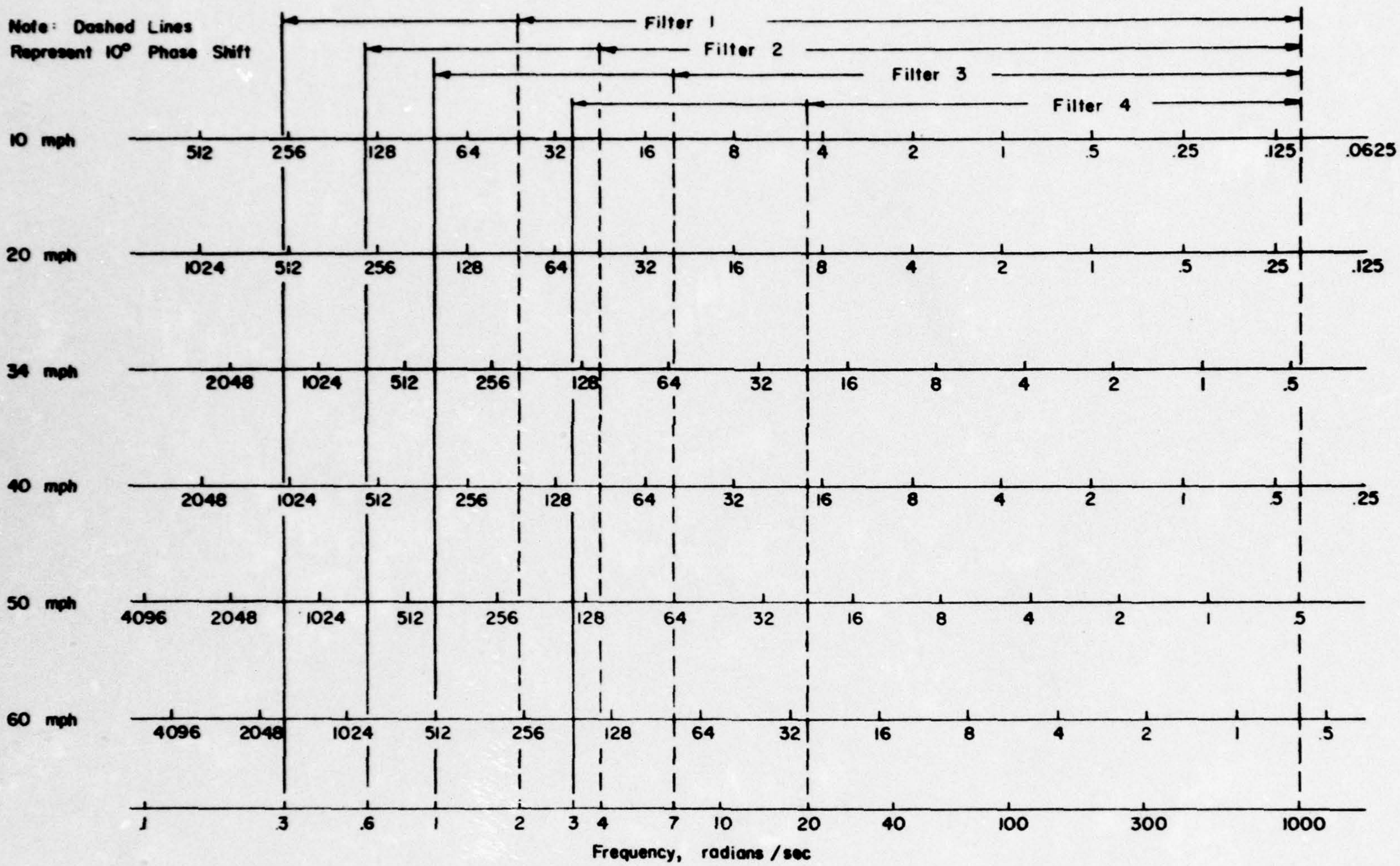
The subsystems affecting the high-frequency response of the Surface Dynamics Profilometer are the same as or analogous to the Air Force Profilometer subsystems.

Potentiometer. Used in place of an LVDT for determining the relative following wheel position, the potentiometer utilized in the surface dynamics profilometer is a plastic film unit with an electrical travel of 12 inches (30.48 centimeters), a linearity of 0.5 percent, and plastic element resolution of 40×10^{-6} inch (1.01×10^{-4} centimeter). Reference 9 states a possible error of 0.060 inch (0.152 centimeter) for full potentiometer travel due to linearity error.



NOTE: For 20 m.p.h. (32.19 Kilometers/hr) (29.3 feet/second), angular frequency (ω) equals that velocity times two pi divided by the wavelength, e.g., 92 radians/second = 2π (29.3)/200.

Fig 3.3. Surface Dynamics Profilometer system frequency response (Ref 14).



NOTE: 1 mph = 1.6093 kilometer/hr

Fig 3.4. Filter-speed-wavelength selection graph, Surface Dynamics Profilometer, 135° phase shift (Ref 13).

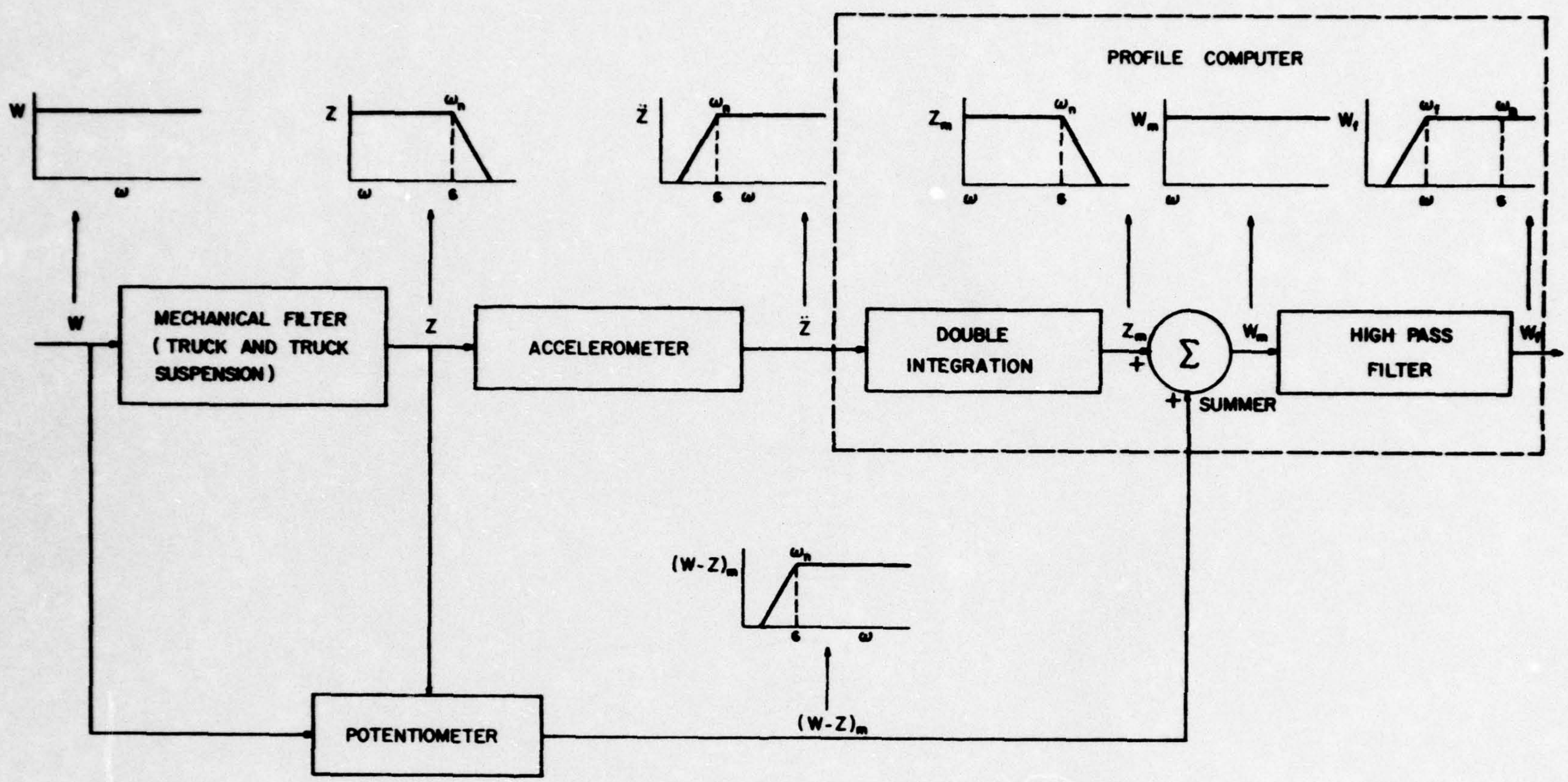


Fig 3.5. Surface Dynamics Profilometer subsystem frequency responses (Ref 13).

Other Limitations. The remaining high-frequency response limitations are identical with limitations present in the Air Force Profilometer. The following wheel size determines the minimum measurable wavelength without considering other system limitations. The following wheel out-of-roundness will produce systematic amplitude errors. The Surface Dynamics Profilometer following wheel is smaller than its counterpart, measuring 5 inches (12.7 centimeters) in diameter, versus 5.7 inches (14.48 centimeters) for the Air Force Profilometer following wheel. Possible errors in the digitization rate are possible due to errors in the sampling pulse. Since the Surface Dynamics Profilometer sampling pulse is generated through the vehicle transmission, a greater possibility of error exists, compared to that of the Air Force Profilometer. The standard digitization rate when the analog data are converted produces digitized data approximately every 2 inches (5.08 centimeters) along the pavement profile. The Nyquist frequency for this interval is in excess of 80 Hz, thus, theoretically allowing detection of wavelengths as small as 4 inches (10.16 centimeters).

Low-Frequency Response

With the exception of possible errors generated by the stabilized platform response time, low-frequency response limitations of the Surface Dynamics Profilometer are identical to those of the Air Force Profilometer. The dominant limitation is also the accelerometer. Deviations of the accelerometer axis from the vertical result in deviations of the measured profile from the true profile. There are two causes for such deviations: erratic motions of the vehicle and changes in profile grade. Sudden accelerations of the vehicle and extreme roughness will cause the vehicle to leave the plane in which the inertial reference is initiated, thus resulting in accelerations measured at an angle not perpendicular to the inertial reference. Changes in grade result in a change of the intertial reference, and, thus, an undefined transition segment is present immediately after such changes. This transition segment is illustrated in Fig 3.6, and has been determined to contain the wavelengths important to aircraft operation (Ref 9).

The characteristics of the accelerometer are also important, The accelerometers used in the Surface Dynamics Profilometer have characteristics similar to those of the Air Force Profilometer accelerometer with the exception of a greater range (± 2g verus ± 1g) required as a result of the

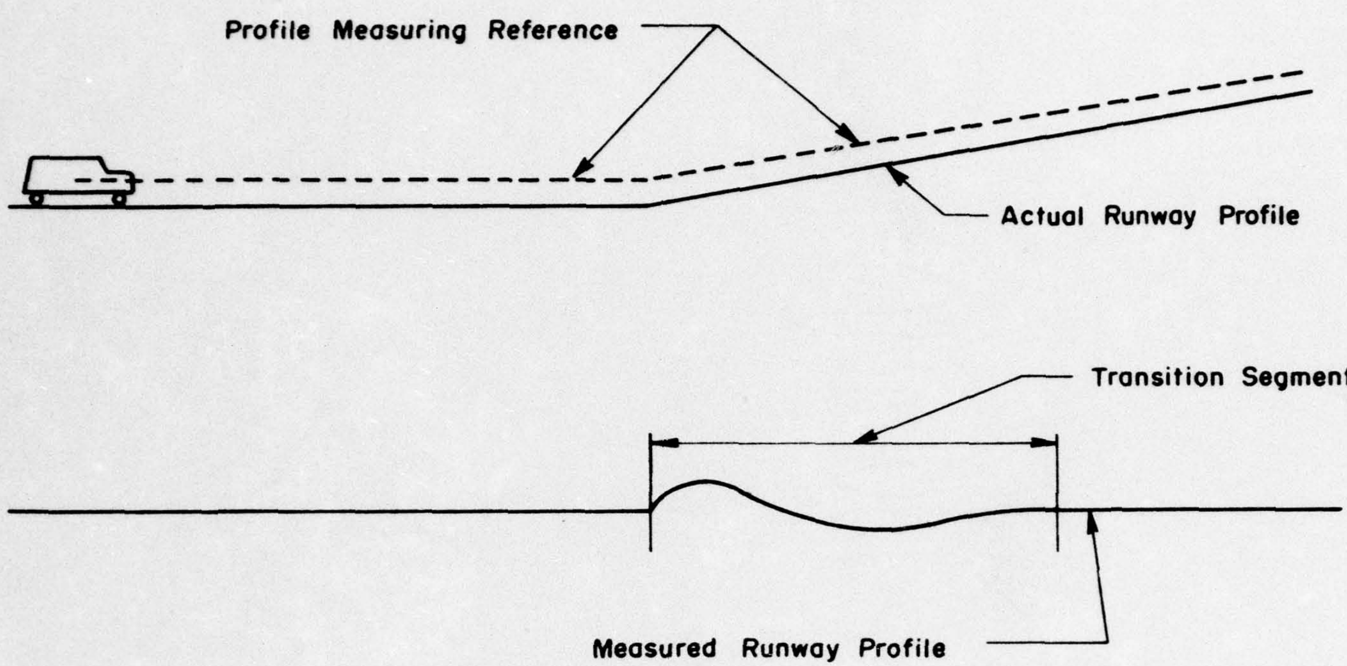
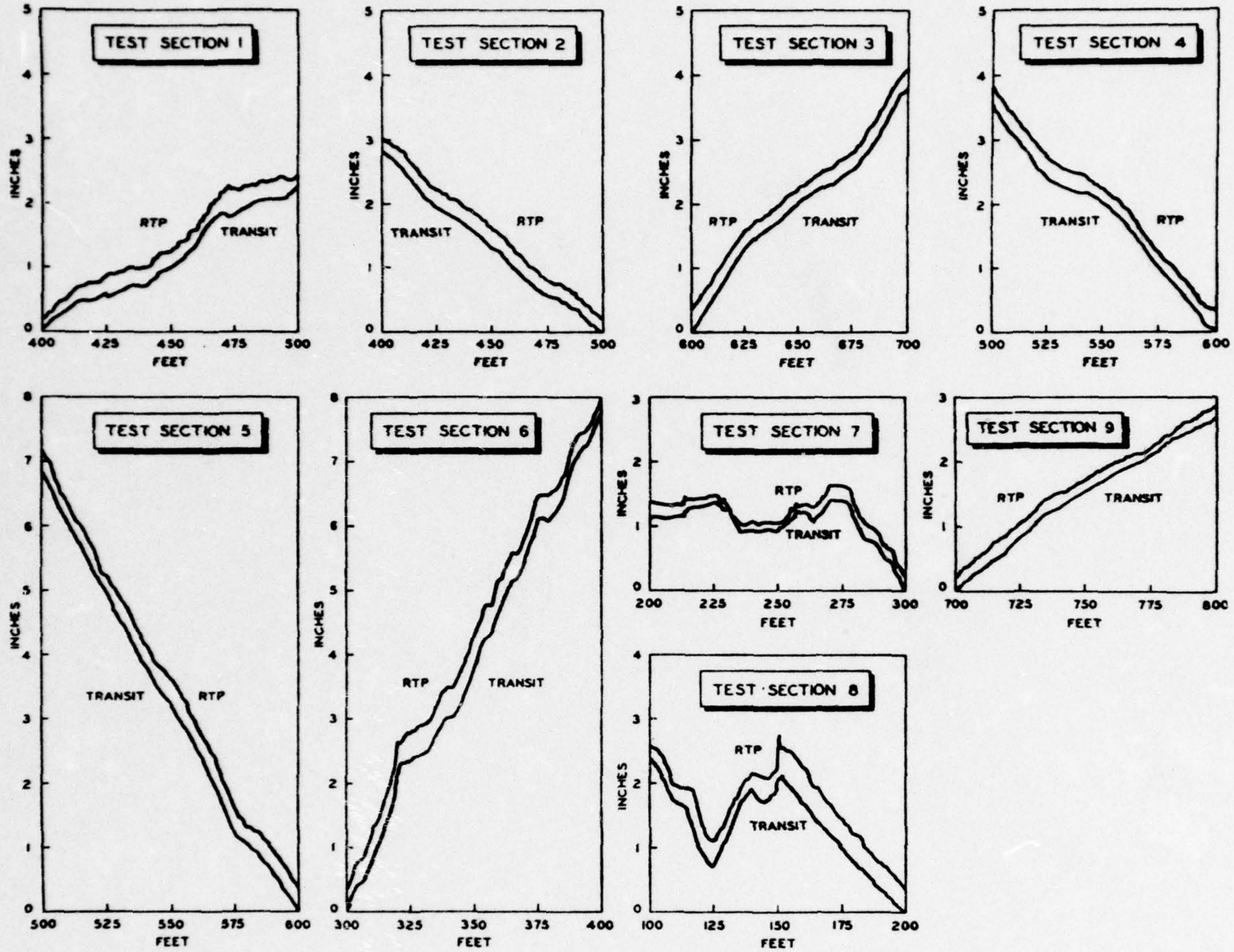


Fig 3.6. Surface Dynamics Profilometer grade change transition segment (Ref 9).

greater accelerations experienced on highway pavements. Reference 9 states that for airfield pavements, where accelerations are small, operation at frequencies much lower than 0.3 radians per second (600-foot (182.87-meter wavelengths at 20 mph (32.19 kilometers/hr)) is possible. The major limitation of low-frequency response, then, is accelerometer tilt error, which is precisely the reason for the stabilized platform provided in the Air Force Profilometer. Electronic noise and drift associated with the profile computer are adequate for normal highway pavement profile measurements. However, Ref 9 reports the development of a special version of the profile computer to provide improved resolution required as a result of normally smaller displacements and accelerations present in airfield pavements. It should be noted that the minimum low-frequency response is determined by selection of the high-pass filter contained in the profile computer.

Observed Accuracy and Operational Characteristics

The last portion of Chapter 3 discussed the results of a verification of Air Force Profilometer accuracy. No similar documentation exists for the Surface Dynamics Profilometer used in this study. The Michigan Department of State Highways (Ref 18) did, however, conduct field tests of the accuracy of their version of the Surface Dynamics Profilometer. Figure 3.7 illustrates their comparison of profilometer and precise rod and level profiles. For visual inspection, the Rapid Travel Profilometer (RTP) profile is elevated 0.2 inch (.508 centimeters) to prevent overlapping. An analysis by direct correlation of 50 to 100-foot (15.24 to 30.48-meter) wavelengths revealed high correlation and low standard error, as summarized in Table 3.1. To analyze 1 to 50-foot (.305 to 15.24-meter) wavelengths, Reference 18 utilized a method of coherence analysis involving power spectra. The results are listed in Table 3.2. The results of the Michigan study indicate the Surface Dynamics Profilometer accuracy to be equal to or greater than that of the Air Force Profilometer. The ultimate criterion of whether or not the Surface Dynamics Profilometer has sufficient accuracy depends on its application. The major application of the Surface Dynamics Profilometer used in this study is in the prediction of riding quality ratings (Present Serviceability Indices) and other research into highway roughness, the results of which indicate more than adequate accuracy.



NOTE: 1 inch = 2.54 centimeters 1 foot = .3048 meters

Fig 3.7. Comparison of Rapid Travel Profilometer and precise level profiles (Ref 18).

TABLE 3.1. LINEAR CORRELATIONS BETWEEN RAPID TRAVEL PROFILOMETER AND PRECISE LEVEL PROFILES (100 FOOT AND 50 FOOT SECTIONS) (REF 18)

Test Section	Slope		One Standard Error, inches		Correlation Coefficient	
	100 Foot	50 Foot	100 Foot	50 Foot	100 Foot	50 Foot
1	0.97	0.88	0.050	0.030	0.997	0.992
2	0.98	1.05	0.034	0.021	0.999	0.999
3	1.00	1.07	0.046	0.021	0.999	0.999
4	0.97	1.02	0.031	0.025	0.999	0.999
5	1.01	1.03	0.044	0.044	0.999	0.999
6	1.02	1.09	0.074	0.044	0.999	0.999
7	0.99	0.99	0.056	0.044	0.082	0.994
8	1.01	0.94	0.096	0.041	0.986	0.998
9	1.05	1.04	0.027	0.028	0.999	0.998

NOTE: 100 feet = 30.48 meters
50 feet = 15.24 meters

TABLE 3.2. COHERENCE VALUES BETWEEN RAPID TRAVEL PROFILOMETER AND PRECISE LEVEL PROFILE (Ref 18)

Wavelength, feet	Frequency, cycles per foot	Coherence Value (Correlation)
50.0	0.02	0.984
25.0	0.04	0.979
16.7	0.06	0.959
12.5	0.08	0.947
10.0	0.10	0.951
8.4	0.12	0.956
7.2	0.14	0.909
6.3	0.16	0.963
5.5	0.18	0.843
5.0	0.20	0.872
4.2	0.24	0.944
3.1	0.32	0.918
2.5	0.40	0.954
2.1	0.48	0.991
1.8	0.56	0.979
1.4	0.72	0.858
1.3	0.87	0.816
1.1	0.91	0.891
1.0	1.00	0.916

NOTE: 1 foot = .3048 meter

Some consideration should be given to some of the operational characteristics of the Surface Dynamics Profilometer. As the Surface Dynamics Profilometer was developed for highway use, it is subject to more wear and tear than if it operated exclusively on airfield pavements. References 13 and 17 report following wheel assembly problems, such as the potentiometer shaft being subject to breakage, excessive damage to or wear of the wheel itself, and wheel bounce on excessively rough pavements. All of these problems have been resolved either by minor modifications or by increased preventive maintenance and care during measurement operations. It should be noted that the Surface Dynamics Profilometer has been accepted by the State Department of Highways and Public Transportation as a working system and is thus no longer considered as only a research tool.

The Surface Dynamics Profilometer system has proven to be a valuable asset, especially in the area of pavement research. Its ease of operation makes obtaining profile data both efficient and economical. Improvements could be made to make it a better system, and thus expand its capabilities; however, the system as it exists is adequate for present utilization.

CHAPTER 4. COMPARISON OF PROFILOMETER SYSTEMS

Having read the previous chapters, one should have an understanding of the basic similarities and differences of the two profilometer systems. There remain, however, more exacting tests of comparison. As such, a field experiment was conducted to analyze the profiles generated by each profilometer.

The Experiment

The original experiment was conceived with an additional purpose in mind, other than comparing the profilometers. This additional purpose was to obtain additional profile data for the AFWL research programs. Considering this factor, it was considered desirable to obtain profile measurements of both highway and airfield pavements. Three profiles were planned for the portland cement concrete primary runway 17 Right (R/W 17R) at Bergstrom AFB, i.e.,

(1) centerline (CL),
(2) right-of-centerline (ROC)
(3) left-of-centerline (LOC).

One profile was planned along the centerline of the parallel asphaltic concrete runway (R/W 35R). Plans also included measurements on both a regularly profiled flexible road section and a rigid pavement bridge deck. The spacings of the measurements on R/W 17R were chosen to be 10 feet (3.05 meters) right and left of the centerline. This spacing approximates the main landing gear spacing of an RF-4 (the primary aircraft using the runway) and a Boeing 727 aircraft. Three replications of each profile were planned for the Air Force Profilometer and two each for the Surface Dynamics Profilometer.

The Air Force Profilometer arrived in Austin, Texas, the first week of April, 1975. As a part of initial familiarization and as a preliminary system check, the outside southbound land of the Loop 1 (MOPAC Expressway) bridge over the Colorado River was profiled on April 17, 1975. At that time, the computer program used to interpret the digital output had not yet been converted to be compatible with The University of Texas at Austin computer

system. There was, therefore, no verification that the data collected were valid. On April 19, 1975, both profilometers were driven to Bergstrom Air Force Base (AFB), on the outskirts of Austin. At approximately 8:00 a.m., measurements were attempted on R/W 17R. Numerous problems ensued. In an attempt to profile as great a length as possible, and specifically the primary touchdown area, each profile measurement required crossing two aircraft arresting system cables (commonly termed barrier cables) stretched transversely across the runway. These cables are approximately one-inch (2.54 centimeters) woven steel and engage a hook on fighter aircraft in an emergency landing. Normally suspended about 6 inches (15.24 centimeters) above the runway surface by neoprene spacers, or "doughnuts," the cables were depressed to the pavement surface by removing the spacers and, if required, by parking vehicles on the cables. It is still unknown whether the severe jolts caused by crossing the cables were a contributing cause to the difficulties experienced.

Two basic difficulties were encountered during this first attempt: failure of the speed control subsystem, and following wheel "wobble." The wheel "wobble" experienced was similar to that of castor type front wheels of supermarket shopping carts. Immediate resolution of these difficulties was not possible, and, thus, profiling efforts were terminated for the day. After replacing the photocell pickup with a spare sent by the AFWL the following week, the speed control subsystem problem was corrected. A decision was also made to restrict measurements to the pavement between the barrier cables. With these adjustments made, profile measurements were successfully accomplished in the early morning hours of April 26, 1975.

Because of uncertainty that the Air Force Profilometer would function properly and because its required return to the Air Force was imminent, the Surface Dynamics Profilometer was left behind, thus dedicating the available time on the runways to the procurement of data with the Air Force Profilometer. It was not until May 24, 1975, that scheduling and operational status of the Surface Dynamics Profilometer permitted the return to the runways for the Surface Dynamics measurements. This delay of almost a month, while unavoidable, is only somewhat regretable. Possible errors introduced by the time lag should be at a minimum because of fairly constant weather conditions during the period. In fact, the temperatures during each morning's measurements were similar, in the low 70's.

Profile measurements of a flexible highway pavement were also made on April 26 with the Air Force Profilometer. The section chosen was Austin Test Section Number 3, which is adjacent to Bergstrom AFB, and therefore conveniently located. The Austin test sections are various sections of typical pavements in the Austin, Texas, area and are profiled regularly with the Surface Dynamics Profilometer. The Surface Dynamics profiles of Test Section Number 3 used in this study were obtained on April 24, 1975.

Runway Measurements

The runway measurements were taken almost as planned, that is, along the centerlines of runways 17R and 35R, and 10 feet (3.05 m.) right and left of the centerline on runway 17R. One measurement at the right of the centerline was only partially completed, due to a landing aircraft, and two rather than three repetitions were made with the Air Force Profilometer on R/W 35R. Reference points were established for each profilometer on R/W 17R as starting and end points of each measurement. For the Air Force Profilometer, each measurement was initiated with the following wheel atop the first transverse joint inside of the barrier cable. The beginning of each section for the Surface Dynamics Profilometer was located at a joint 200 feet (60.96 meters) farther down the runway and was marked with white paint to activate the photocell, signaling the start of data acquisition. Corresponding endpoints were located as illustrated in Fig 4.1. The first 200 feet (60.46 m.) of each Air Force profile (where the Air Force Profilometer was accelerating) were discarded, resulting in the same starting point for each profilometer. The Air Force profile measurements were terminated at the same joint as the surface dynamics profiles; however, after decelerating, the Air Force Profilometer was moved forward until the following wheel was atop the joint immediately prior to the second barrier cable. The total distance, as measured, was then recorded. These values indicated a "wander" error of approximately 30 feet (9.14 m.), or 0.3 percent, over the actual distance of 10,275 feet (3131 meters). The actual distance was obtained from engineering drawings provided by the Base Civil Engineer at Bergstrom AFB. As there are no direct distance measurements made with the Surface Dynamics Profilometer, profiling was simply terminated at the designated stopping point.

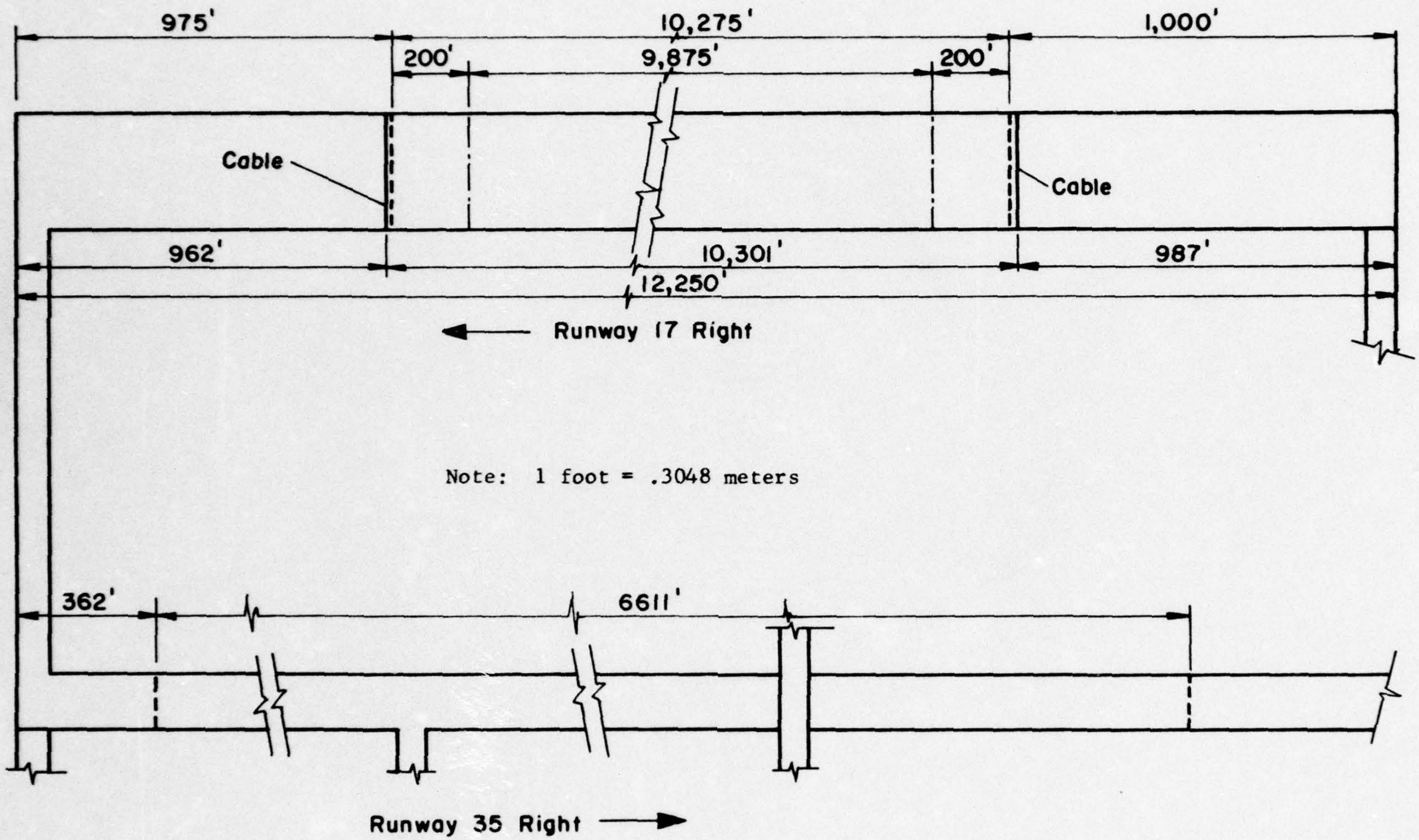


Fig 4.1. Locations of profiled runway sections.

The "wander" error of each profilometer is compounded by the digitizing process and the computer programs utilized to unpack the condensed digital data as originally recorded. As a result, the 9875-foot (3010-meter) profile section as measured by the Surface Dynamics Profilometer became 10,133 feet (3088 meters) long, an error of 2.6 percent. Subtracting the first 200 feet (60.96 meters) of the Air Force profile and the portion past the endmark leaves profiled sections measuring 9,910 feet (3020 meters), or an error of 0.3 percent, which is consistent with the previous result. It is believed a major portion of the difference between the measured lengths can be attributed to having each profilometer driven by a different driver; also, the Surface Dynamics Profilometer driver was responsible for speed control as well as steering.

Profile measurements of the centerline of runway 35R were initiated at the start of the centerline marking and continued to a transverse mark indicating the runway threshold (See Fig 4.1). Both profilometers accelerated to 20 mph (32.19 kph) prior to initiating measurements. Again, measured distances differed from the actual distance of the section. The actual distance of 6611 feet (2015 meters) was measured utilizing station markings placed on the centerline for an impending maintenance contract. The profile as measured by the Surface Dynamics Profilometer was 6840 feet (2085 meters) long, an error of 3.4 percent. The section as measured by the Air Force Profilometer was 6640 feet (2024 meters) long, an error of 0.4 percent. The errors in length for both profilometers are greater for this flexible pavement section than they were on the rigid pavement sections, most likely due to the lack of longitudinal joints as reference points for the driver. In any case, the increase is negligible.

Road Section Measurements

Two road sections were profiled with the Air Force Profilometer for comparison purposes. The accuracy of the previously mentioned measurements of the Loop 1 (MOPAC Expressway) bridge became suspect when the first attempts of profiling R/W 17R were unsuccessful. In addition, proper control of the section was extremely difficult as the Surface Dynamics Profilometer measurements had been taken prior to the opening of the bridge to traffic and in the opposite direction. More recent measurements with the Surface Dynamics

Profilometer were not taken because the Air Force Profilometer had to be returned to the AFWL before measurements could be reaccomplished. Comparison of the two profilometers for highway pavement sections was, therefore, limited to flexible pavement.

.The flexible pavement section used in this study is an 1140-foot (348-meter) portion of the northbound lane of Farm-to-Market Road 973, north of the Burleson Road intersection. The 1140-foot (348-meter) length was chosen primarily as a convenience, since nine records of Surface Dynamics Profilometer digital data contain 1140 feet (348 meters). The digital files of the Surface Dynamics profiles were 1140 feet (348 meters) long, while the lengths of the Air Force profiles were 1152 and 1280 feet (351 and 390 meters). The Air Force profile was obtained in the same manner as that for the centerline of R/W 35R. The excess lengths are due more to the initiating and terminating of the data taking than to vehicle wander. The greatest difficulty in profiling this section with the Air Force Profilometer for comparison purposes was in locating the following wheel in the normal right wheelpath of traffic. Since the Surface Dynamics Profilometer following wheels are in the vehicle wheelpaths, the Air Force Profilometer had to be consistently driven to the right of the normally traveled vehicle path. The profiles obtained for this section demonstrate this difficulty, as will be discussed later in this chapter.

Characterization of the Profiles

In order to accurately compare the profiles produced by each profilometer, each system's output must be handled in the same manner. So that this could be done, an existing digital computer program named ROKYRD (for "Roky Road") was modified from being able to handle the standard surface dynamics road data so that it could handle the differently arranged airfield profiles. The modified program, named ROKRUN (for "Rocky Runway"), is listed in Appendix 1. An extensive input guide is included at the beginning of the program.

The major modification made for ROKRUN was to change the normal left profile input of the Surface Dynamics Profilometer from the left wheelpath of a right-of-centerline data file to the right wheelpath of a left-of-centerline data file (all surface dynamics profiles were made with the right following wheel). Since the Air Force profile data are encoded differently, they were decoded separately and saved on both magnetic tape and

punched cards. The subroutine to read in the profile was thus changed to utilize either the standard digital magnetic tape of surface dynamics data, or the card-formatted Air Force profile data. Two other modifications were necessitated by the desire to compare visually plots of the profiles produced by each system. With differences in measured lengths and, as was discovered, in profile amplitudes, the automatic scaling of the X and Y axes had to be negated and scaling for each axis forced. Also, due to the stabilized platform of the Air Force Profilometer, the raw, unfiltered Air Force profiles ranged from zero elevation to -200 inches (-508 centimeters). With such a large range, it was necessary to provide an option to plot only filtered profiles, where the range of profile amplitudes is similar.

The ROKYRD and ROKRUN computer programs characterize the pavement profile through the use of a recursive digital filtering routine which isolated surface irregularities in specified adjacent passbands. In addition, ROKRUN offers the option of using the digital filtering routine utilized by the AFWL. Moving mean square values of profile amplitude are calculated for the right, left and the pointwise difference profiles within each specified passband. Then, quoting the input guide, "the mean, standard deviation, approximating discrete probability density and distribution functions, and the 50, 75, 90, 95, and 99th percentile points are computed for each set." Table 4.1 is an example of typical output from ROKRUN. Highway Serviceability Index (SI) values for each section are also calculated using a model developed in Ref 19, if certain passbands are specified.

Seven passbands were selected for this study, i.e., 4 to 10, 10 to 25, 25 to 50, 50 to 100, 100 to 200, 200 to 400, and 3 to 200 feet (1.2 to 3.1, 3.1 to 7.6, 7.6 to 15.2, 15.2 to 30.5, 30.5 to 61.0, 61.0 to 121.9, and .9 to 61.0 meters). The first four passbands are those normally considered for highway pavements. The 100 to 200 and 200 to 400 foot (30.5 to 61.0 and 61.0 to 121.9 meter) passbands were added to include wavelengths that are important to aircraft response, which, from experience with instrumented aircraft and simulated aircraft response, range from 4 or 5 feet (1.2 or 1.5 meters) to approximately 350 feet (106.7 meters) (Refs 7 and 20). A separate, overall passband of 3 to 200 feet (.9 to 61.0 meters) was considered to compare the profilometers in a broader respect, similar to the comparison of the two Air Force Profilometers cited in Ref 7. It should be noted that the overall passband was cut off at 200 (61.0) rather than 400 feet (121.9 meters) due to

TABLE 4.1. ROUGHNESS AMPLITUDES AS CHARACTERIZED BY PROGRAM ROKRUN

BERGSTROM AFB R/W 17R SECTION A SD PROFILOMETER 24 MAY 1975 FILE 1
SUMMARY STATISTICS FOR ROUGHNESS AMPLITUDES (IN.)

0.0 TO 4.0 FT. WAVELENGTHS

	STANDARD DEVIATION	MEAN	PERCENTILE 50	75	90	95	99
RIGHT PROFILE	.00387	.00935	.00876	.01147	.01450	.01649	.02081
LEFT PROFILE	.00481	.01055	.00955	.01259	.01669	.01985	.02700
DIFF. PROFILE	.00603	.01463	.01370	.01734	.02250	.02615	.03482

4.0 TO 10.0 FT. WAVELENGTHS

	STANDARD DEVIATION	MEAN	PERCENTILE 50	75	90	95	99
RIGHT PROFILE	.00478	.01172	.01095	.01435	.01820	.02083	.02644
LEFT PROFILE	.00629	.01438	.01315	.01802	.02354	.02683	.03182
DIFF. PROFILE	.00638	.01701	.01606	.02071	.02603	.02942	.03417

10.0 TO 25.0 FT. WAVELENGTHS

	STANDARD DEVIATION	MEAN	PERCENTILE 50	75	90	95	99
RIGHT PROFILE	.00896	.02307	.02119	.02856	.03559	.04015	.04727
LEFT PROFILE	.00648	.02208	.02184	.02613	.03074	.03366	.03913
DIFF. PROFILE	.01002	.02993	.02940	.03590	.04305	.04830	.05557

25.0 TO 50.0 FT. WAVELENGTHS

	STANDARD DEVIATION	MEAN	PERCENTILE 50	75	90	95	99
RIGHT PROFILE	.01152	.03157	.03041	.03984	.04837	.05158	.06000
LEFT PROFILE	.01413	.03504	.03319	.04299	.05698	.06144	.07693
DIFF. PROFILE	.01538	.04073	.04007	.05146	.06178	.06826	.08035

50.0 TO 100.0 FT. WAVELENGTHS

	STANDARD DEVIATION	MEAN	PERCENTILE 50	75	90	95	99
RIGHT PROFILE	.02600	.04405	.03881	.05396	.06099	.10758	.14100
LEFT PROFILE	.02758	.04973	.04266	.05810	.07209	.11903	.15493
DIFF. PROFILE	.01476	.05599	.05227	.06526	.07938	.08445	.09002

100.0 TO 200.0 FT. WAVELENGTHS

	STANDARD DEVIATION	MEAN	PERCENTILE 50	75	90	95	99
RIGHT PROFILE	.11765	.10888	.05676	.10350	.34502	.40865	.43886
LEFT PROFILE	.05553	.07405	.05042	.09036	.18075	.20635	.22572
DIFF. PROFILE	.05315	.07102	.04771	.08277	.17248	.21159	.21849

200.0 TO 400.0 FT. WAVELENGTHS

	STANDARD DEVIATION	MEAN	PERCENTILE 50	75	90	95	99
RIGHT PROFILE	.10732	.15966	.12387	.25372	.34543	.35557	.35976
LEFT PROFILE	.03050	.10960	.10504	.12910	.15944	.16440	.16637
DIFF. PROFILE	.05052	.10402	.07618	.13895	.18825	.20042	.20187

S I V A L U E S

THIS PVMT SECTION IS RIGID PAVEMENT OF TYPE JRCP

ALL PASSBANDS CONSIDERED: 4.2124

PASSBAND	COMBINED	TRANSVERSE	LONGITUDINAL
4.0 TO 10.0 FT.	3.9466	4.0663	4.0807
10.0 TO 25.0 FT.	4.0433	3.7925	4.2501
25.0 TO 50.0 FT.	3.7898	3.6316	4.1787
50.0 TO 100.0 FT.	3.7199	3.8801	4.2570

high-pass filtering in the surface dynamics profile at wavelengths greater than 200 feet (61 meters). Applying the operating speed of 20 miles per hour (32.19 kph) and the use of high pass filter 1 to Figs 3.3 and 3.4, one anticipates a maximum wavelength capability of 200 feet (61.0 meters) with no attenuation and a 45° phase shift, and very little attenuation, but approximately a 105° phase shift for 400-foot (121.9-meter) wavelengths. The 3 to 200-foot (.9 to 61.0-meter) passband was also utilized in order to provide an adequate number of graphical profiles for visual comparison, rather than the excessive number of plots which would be required if the individual passbands from 4 to 400 feet (1.22 to 121.9 meters) were utilized. With the exception of Austin Test Section Number 3, the lines of survey were divided into sections (A, B, C and D for R/W 17R and A, B, and C for R/W 35R). This sectioning was accomplished primarily due to the profile array size in ROKRUN, but also to provide a larger amount of data for statistical analysis.

The characterizations of the profiles are, however, limited. While an analytical comparison of roughness amplitudes provides indications of each profilometer's response, the lack of a true reference profile restricts what can be concluded concerning the accuracy of the profilometers. Such a reference profile, as might be determined from a rod and level survey or by the Air Force's laser profilometer, was not available for this study, and therefore it is not known which profilometer's profile is more correct.

Profile Analysis

When comparisons of profiles are considered, two general methods become obvious. A visual comparison of plotted profiles can be informative, however, conclusive statements concerning such comparisons are only generalizations and are limited by the accuracy or resolution, and the size or scales used in plotting the profiles. Much more meaningful conclusions can be drawn using statistical inference. Both visual and statistical comparisons are documented in the following sections.

Visual Comparison. Because it is believed that the ancient adage that "a picture is worth a thousand words" is true, Appendix 2 contains plotted profiles for the various pavement sections profiled with the Air Force and Surface Dynamics Profilometers. Figures A2.1a through A2.8c illustrate the rigid pavement sections on R/W 17R, while Figs A2.9a through A2.12c are the

flexible pavement section profiles. Inspection of the profiles for the rigid pavement sections indicates, in general, good agreement between the two profilometers. Major or extreme profile peaks basically correspond with each other, yet slight differences in their lateral locations demonstrate the differences in the wander of the profilometers. The most obvious differences in the two measured rigid pavement profiles are at the beginnings of sections C and D (Figs A2.5a, .6a, .7a, and .8a) where the Air Force Profilometer measured greater long wavelength amplitudes.

Closer inspection of the profile plots for R/W 17R reveals somewhat more subtle differences. Within large waveforms, small amplitude changes in profile elevation differ, and, in general, the surface dynamics profiles have greater amplitudes. Another interesting observation is the difference between the profiles of each section. Sections B and C (Figs A2.3, .4, .5, and .6) in the middle of the runway exhibit a more uniform profile than do the end sections, A and C. It should be noted that Figs A2.3 and .4 have a vertical scale twice as large as the other plots of R/W 17R. Also interesting is the expected similarity of right-of-center and left-of-center profiles (e.g., A2.1b versus A2.2b and A2.5c versus A2.6c).

Figures A2.9a through A2.12c illustrate each profilometer's response to flexible pavement; Figs A2.9, .10 and .11 are of the Runway 35 Right centerline, while Fig A2.12 is the right wheelpath of Austin Test Section Number 3. A visual inspection of these figures reveals much more significant differences than for rigid pavement. Although general forms of the profiles are similar, the Surface Dynamics profiles seem to contain more short-wavelength roughness and have larger amplitudes than the Air Force profiles. This is evidenced by the more jagged characteristics and the amplitudes of the largest peaks of the Surface Dynamics profiles.

The differences noted, however, are reasonable. Even with a location error similar to that of rigid pavement, the transverse variation of a flexible pavement profile is increased simply because the pavement is flexible. One cannot expect a comparison of profiles on flexible pavement to be as good as might be expected on rigid pavement. Difficulties in following the same profile paths on the flexible pavements were mentioned previously. The comparison of the profile plots for these sections reinforces the supposition that comparisons for flexible pavement would be somewhat poor.

The profile plots contained in Appendix 2 are not a complete set of all possible combinations of pavement type, section, and repetition. They are, however, illustrative examples intended to provide insight to further comparison of the profilometers.

Statistical Analysis. Although visual comparisons of pavement surface profile plots are very informative, several statistical techniques are available for use in comparing the Air Force and Surface Dynamics Profilometers. Of interest is a comparison of the mean roughness amplitudes as measured by each profilometer and characterized by the ROKRUN computer program.

Several statistical techniques are available with which one can test for significant differences. Since the variables of interest are means of roughness amplitudes, a comparison of profilometers can be achieved by testing the difference between the means of the mean roughness amplitudes measured with each instrument. The hypothesis we wish to test is, thus,

$$\mu_{SD} = \mu_{AF}$$

where

μ_{SD} = the mean of root mean square (r.m.s.) roughness amplitudes as measured by the Surface Dynamics Profilometer,

μ_{AF} = the mean of r.m.s. roughness amplitudes as measured by the Air Force Profilometer.

A null hypothesis of equal means and a corresponding alternate hypothesis of unequal means ($\mu_{SD} \neq \mu_{AF}$) can be tested by various methods. Since the universe standard deviations are unknown, the t statistic could be used, however, this would be an inefficient comparison and difficult to interpret. A much more efficient and powerful means of testing the hypothesis is an analysis of variance (ANOVA).

The use of ANOVA, though actually a comparison of the variances, provides an objective criterion with which to decide, " ... whether the variability between groups is large enough in comparison with the variability within groups to justify the inference that the means of the populations from which

the different groups were drawn are not all the same" (Ref 21). So, in order to test the hypothesis that $\mu_{SD} = \mu_{AF}$, an ANOVA tests the relationship of the variances of r.m.s. roughness amplitudes as determined by each profilometer.

On the basis of the available data, and their restrictions, the statistical comparison was designed as illustrated in Fig 4.2. Separate ANOVA's were planned for each wavelength passband and for each type of pavement. The separation according to pavement type was based on the visual comparison of profiles and accomplished in order to isolate the anticipated poor comparison caused by survey line following error. All data as provided by ROKRUN are presented in Appendix 3. Asterisked values indicate data eliminated from the ANOVA. These values were all Air Force Profilometer data and were eliminated due to obvious differences in their magnitude.

The available data indicated a two-way ANOVA would be applicable, as two factors contribute to the values of roughness amplitudes (i.e. profilometer and section). The ANOVA's were accomplished with a computer program for a two-way unequal cell ANOVA available from the statistical library of the Center for Highway Research. The program utilizes a non-additive model as follows:

$$y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \epsilon_{(ij)k}$$

where

μ = overall mean,

α_i = row effect term,

β_j = column effect term,

$(\alpha\beta)_{ij}$ = interaction term,

$\epsilon_{(ij)k}$ = experimental error.

ANOVA results for the rigid pavement sections are tabulated in Tables A3.5 through A3.11. Note that because the majority of roughness amplitudes were less than one inch (2.54 centimeters), all values were transformed (multiplied by 1000), thus resulting in sum of squares and mean square values multiplied by one million.

Pavement				Rigid												Flexible			
Location				Runway 17 Right												Runway 17 Right			Austin No. 3
Survey Line				Centerline				Right-of-Center				Left-of-Center				Centerline			Right ℄ Wheel Path
Section				A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	
Passband	4-10	Profilometer	SD																
			AF																
	10-25		SD																
			AF																
	25-50		SD																
			AF																
	50-100		SD																
			AF																
	100-200		SD																
			AF																
	0-400		SD																
			F																

2 Observations per SD cell
3 Observations per AF cell

2 Observations per cell

The "a" portion of each table contains these transformed sum of squares and mean square values. The F Ratio is unaffected, as the multiplying factors cancel out. The "b" portions of these tables contain the cell means for each profilometer as well as the percent difference between the cell means. Each pavement section (1-11) is also identified by line of survey (e.g., CL-A = centerline, section A; ROC-B = right-of-center, section B).

Inspection of Tables A3.5 through A3.11 reveals widely varying F ratios for the effects of profilometer used and for interaction between the pavement section and profilometer. In all cases, there are significant differences in roughness amplitudes between pavement sections, as was expected. For convenience, the F ratios for profilometer and interaction effects are summarized in Table 4.2. The F ratios from ANOVA for the flexible pavement sections are included in Table 4.2, but because of the obvious significance of all but two values, no other ANOVA results for flexible pavement are presented.

Interpretation of ANOVA Results. When the results of an ANOVA are interpreted, care must be taken to avoid erroneous conclusions. This is especially true when significant interaction of the main effects is present. Such is the case for the ANOVA results presented.

In testing the significance of the main effect of profilometer type for a level of significance of 0.05, systematic differences between the two profilometers exist in the third, fourth, and sixth passbands (for the time being, the F ratio for the fifth passband will be considered as non-significant). With the exception of the sixth passband, where known differences exist due to the frequency response of the Surface Dynamics Profilometer, the interaction effect is not significant for the passbands showing significant profilometer differences. This lack of interaction indicates that the differences between the profilometers are the same from pavement section to pavement section. Conversely, for the first, second, fifth, and seventh passbands, where the F ratios indicate no systematic differences between the two profilometers, there are significant interaction effects. The presence of an interaction effect indicates that differences between the profilometers are not systematic from pavement section to pavement section.

TABLE 4.2. SUMMARY OF F RATIOS

Pavement		Rigid		Flexible	
Effect		Profilometer	Interaction	Profilometer	Interaction
Passband Number	Feet				
1	4 to 10	1.98	6.48*	2481.82*	33.57*
2	10 to 25	0.88	7.27*	119.50*	0.89
3	25 to 50	66.70*	1.06	1191.28*	84.76*
4	50 to 100	58.71*	0.83	125.83*	10.06*
5	100 to 200	4.28**	2.49*	8.14*	1.35
6	200 to 400	73.88*	6.57*	1436.44*	579.01*
7	3 to 200	0.10	2.16***	9.46*	16.06*

Critical F Ratios

Degrees of freedom	1,28	10,28	1,8	3,8
α = 0.05	4.20	2.19	5.32	4.07

*Significant at α = 0.05 level

**Bordering on non-significant at 0.05 level

***Bordering on significant at 0.05 level

NOTE: 1 foot = .3048 meters

The interaction effect upon the differences in measured roughness amplitudes is plainly evident in plots of cell means for the various passbands (Figs 4.3 and 4.4). These figures show that with significant interaction there is crossing over in the plots. Utilizing Tables A3.5 through A3.11 and Figs 4.3 and 4.4, the following observations are made:

(1) With the exception of the middle passbands (25 to 50 and 50 to 100 feet) or (7.62 to 15.24 and 15.24 to 30.5 meters), the Air Force Profilometer generally measured greater roughness amplitudes along the centerline of Runway 17 Right.

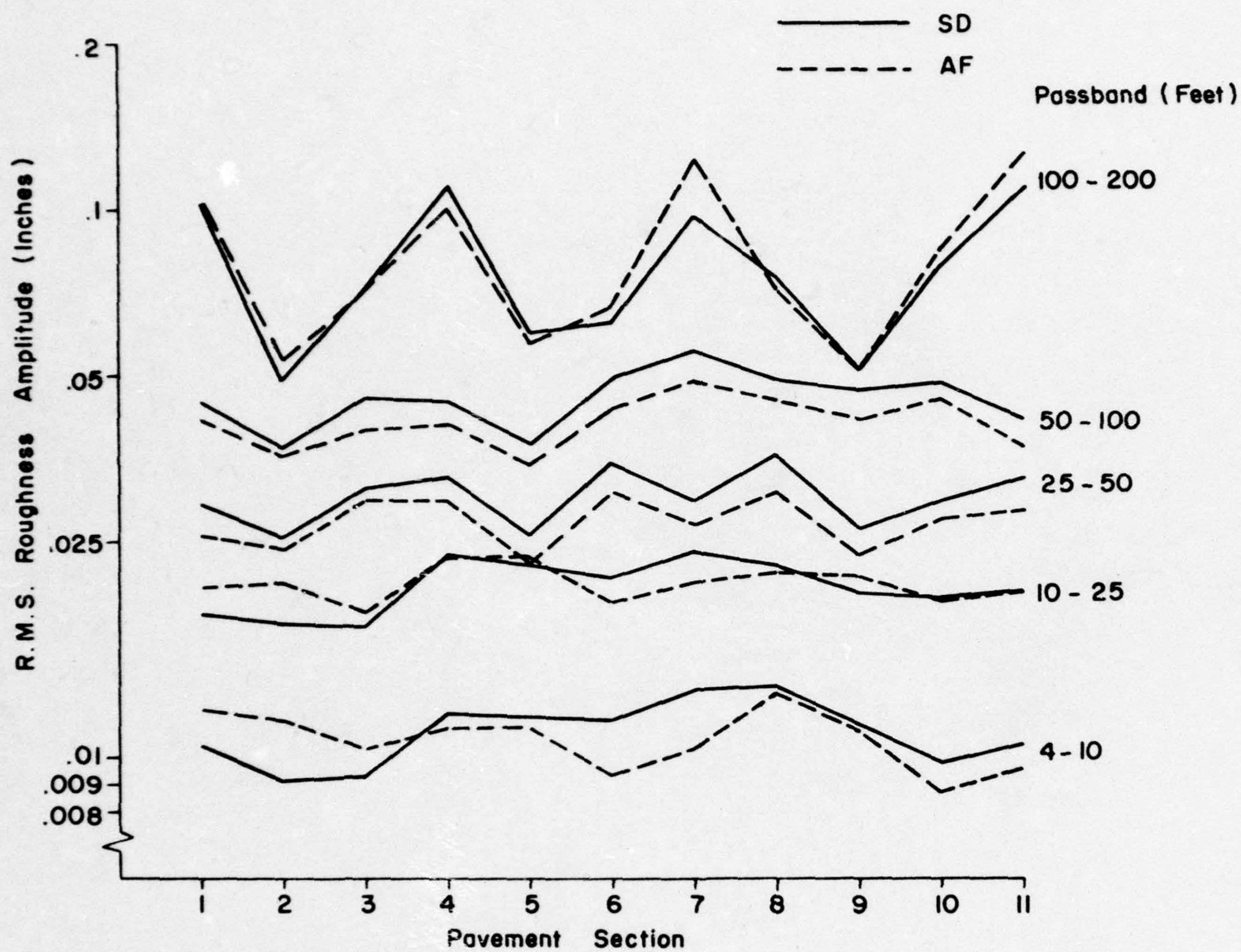
(2) The differences between the profilometers are fairly consistent for the same two middle passbands along the right and left-of-center survey lines.

(3) Figure 4.3 shows that the Air Force Profilometer generally measured higher amplitudes than the Surface Dynamics Profilometer where roughness was relatively large and lower where roughness was relatively small.

(4) In general, the middle sections of the survey lines exhibit lower roughness amplitudes than the end sections.

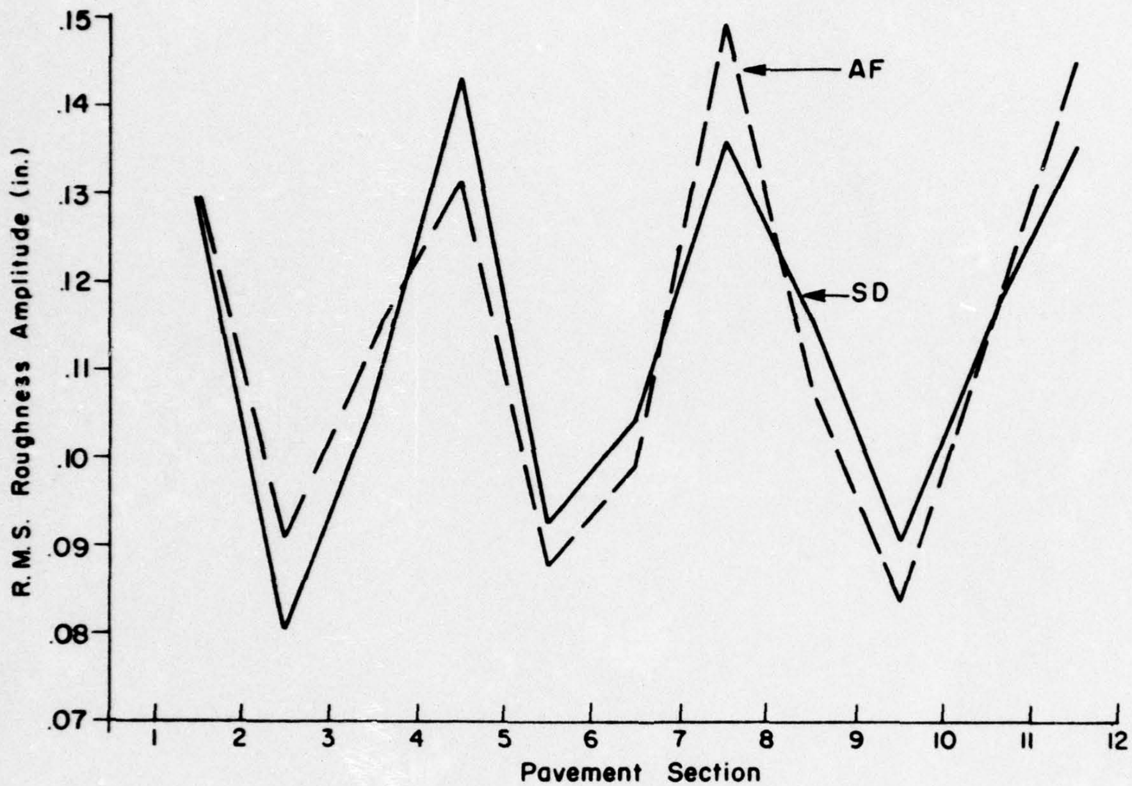
Significant interactions are present in four of the six individual passbands. This means that measurable differences exist between the profilometers, but the differences are dependent on the section measured (the roughness encountered) and, therefore, are not systematic or consistent. Significant differences between the profilometers exist for the remaining individual passbands. It can therefore be stated that measurable differences exist between the two profilometers when considering individual passbands. It should be noted, however, that the relative magnitudes of the differences are small and are due in part to the excellent repeatability of each profilometer. When considering the overall 3 to 200-foot (.91 to 60.96-meter) passband, neither significant difference nor interaction is indicated (though the interaction F ratio borders on significance), thus implying no measurable systematic differences between the profilometers for a broad overall passband.

Further comparison of the profilometers can be accomplished by comparing the results of the applications of their profile data. At present, there are two applications of profilometer data in the area of pavement roughness evaluation. The first application is the use of Surface Dynamics Profilometer generated data in mathematical models for determining highway serviceability index values. The other application is as an input for the AFWL aircraft response simulation program. If, as in the case of the comparison of the two



NOTE: 1 inch = 2.54 centimeters
1 foot = .3048 meters

Fig 4.3. Plots of cell means, rigid pavement, individual passbands.



Filter Passband : 3.0 to 200.0-Foot Wavelengths

NOTE: 1 inch = 2.54 centimeters
1 foot = .3048 meters

Fig 4.4. Plots of cell means, rigid pavement, overall passband.

Air Force Profilometer systems cited in Ref 7, the profiles of the two profilometers resulted in equal or similar aircraft responses, the Air Force and Surface Dynamics Profilometers could be stated to be equivalent, since the final output desired was the same. Similarly, if serviceability index values determined by each profilometer are similar, the profilometers could again be called equivalent.

It was not feasible to input all the profiles into an aircraft response simulation, and, thus, it is not known whether this type of end result would indicate profilometer equivalence. There were, however, as part of the characterization of the profiles by ROKRUN, serviceability index values resulting from each profilometer. Although ROKRUN determines combined, transverse, and longitudinal SI values for each passband (see Table 4.1), the end results, or all passbands considered SI values, and can be compared to determine the comparability of the profilometers. A set of such SI values for each profilometer is listed in Table 4.3a. Inspection of these values as well as the average values in Table 4.3b indicates close agreement between the values from each profilometer. It should be noted that, although an ANOVA of these values indicated significant differences, the precision of the values is greater than that of performance panel ratings. Reference 19 indicates that for an adequately large rating panel, the standard deviation of the mean panel rating is 0.1. The difference between profilometer-determined serviceabilty indices is less than 0.1 in all cases. We can therefore state that either profilometer will predict the panel rating with the same accuracy. The accuracy of the serviceability indices versus the ratings is of course limited by the accuracy of the model used to predict the ratings.

One conclusion can be drawn from the results of the comparison at this point. For rigid pavements, the Air Force and Surface Dynamics Profilometers are comparable, because overall serviceability indices determined by each profilometer are comparable. This statement thus implies that, if equipped with two following wheels, the Air Force Profilometer could be used with confidence to determine rigid highway pavement serviceability indices. Similar conclusions concerning the comparability of the profilometers as they might apply to airfield pavements and flexible pavements cannot be drawn for several reasons. The model used to determine serviceability indices

TABLE 4.3a. RUNWAY 17 RIGHT, SERVICEABILITY INDICES*

Profilometer	Runway Section			
	A	B	C	D
Surface Dynamics	4.2124 4.2339	4.2997 4.2957	4.3194 4.2758	4.2670 4.2596
Air Force	4.2743 4.3072	4.2635 4.2704	4.3370 4.3608	4.3128 4.3083

*Two repetitions for each section and profilometer

TABLE 4.3b. RUNWAY 17 RIGHT, AVERAGE SERVICEABILITY INDICES

Surface Dynamics	4.2232	4.2977	4.2976	4.2633
Air Force	4.2908	4.2669	4.3489	4.3106

does not include the longer wavelength information applicable to airfield pavements. It is therefore unknown whether differences in these longer wavelengths would negate the favorable comparison of SI values as might be determined for airfields. Also, without results of an aircraft response simulation from each profilometer, nothing can be said of how comparable results are when the profiles are considered as a whole. Conclusions cannot be drawn concerning flexible pavement response, due to the inadequacy of flexible pavement results for this study.

It was previously mentioned that flexible roughness amplitudes for all passbands differed significantly. One might conclude then that the two profilometers do not compare on flexible pavement. This would be a hasty conclusion. It was also previously mentioned that greater difficulty in following the flexible pavement survey lines would play a role in comparing the profilometers on flexible pavement. It is believed that the significant differences are primarily due to the error associated in following the same survey line with each profilometer. It is, therefore, reasonable to assume that with better control of transverse location, improved results could be obtained for flexible pavement.

CHAPTER 5. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The major points of the comparison of the Air Force and Surface Dynamics Profilometers are summarized below. The background information presented in Chapter 1 is also included for completeness and for the convenience of the reader.

Background

(1) Compared to the highway pavement case, relatively little has been accomplished in applying the serviceability-performance concept to airfield pavements.

(2) This is partially due to the difficulty in defining just what constitutes failure of an airfield pavement and the greater complexity of the airfield pavement case.

(3) The United States Air Force Weapons Laboratory is presently engaged in research to quantify runway roughness. To do so, two profilometer systems have been utilized:

- (a) a laser reference system and
- (b) an inertial reference system similar in concept to the Surface Dynamics Profilometer developed for highway pavement research.

(4) For the benefit of both highway and airfield pavement research, the two inertial reference profilometers are being compared with respect to their basic characteristics and outputs.

Characteristics of the Profilometer Systems

In the following section, the basic similarities and differences of the systems are noted.

(1) Both systems measure surface profiles based on the principle of a mechanical vibrometer (Fig 2.2) utilizing accelerometers to gather long wavelength information and linear displacement devices to collect short wavelength information.

(2) Designed for use on airfield pavements, the Air Force system has only one contour following assembly, and it includes a stabilized accelerometer platform, while the Surface Dynamics Profilometer has two following wheels, one in each wheelpath, with no stabilized platforms.

(3) The Air Force Profilometer data are in digital form, whereas the Surface Dynamics analog or continuous output must be converted to digital form in a separate operation.

(4) The Surface Dynamics Profilometer requires two operators versus the three required for the Air Force Profilometer, where steering and speed control responsibilities are separated.

(5) In addition to limitations of individual components, the frequency response of each system is limited:

(a) by the operating speed and high-pass filter selection of the Surface Dynamics Profilometer and

(b) to the design response region of 3 to 400-foot (.9 to 121.9-meter) wavelengths for the Air Force Profilometer.

Summary and Conclusions of the Comparison Experiment

The output of each system was compared both visually and statistically. The visual comparison of plotted profiles from each system indicated a favorable comparison for rigid pavement but only a basic similarity for flexible pavement. Statistical analysis revealed measurable differences between the two profilometers for individual narrow passbands but not for an overall broad passband. The actual observed differences are relatively small, and produce very small differences in serviceability indices computed from each system's output. The differences between the profilometers are more an indication of the excellent repeatability of each system than of anything else. The results of the comparison, therefore lend credibility to both systems.

The comparison is summarized below in further detail.

(1) Visual comparison of plotted profiles indicated that:

(a) for the rigid pavement of Runway 17 Right, a favorable comparison existed when the profiles were superimposed upon each other. Major peaks and their general shapes basically correspond to each other. Subtle differences exist within the large waveforms; however, surface dynamics profiles have slightly greater amplitudes for the files plotted.

(b) for flexible pavements, there is a notable lack of similarity. Although the general forms are similar, the Air Force profiles lack the shorter wavelength roughness present in the surface dynamics profiles.

(2) Varying degrees of difference were noted in the statistical analysis of rigid pavement mean roughness amplitudes.

(a) Significant differences were indicated for the 25 to 50 and 50 to 100-foot (7.6 to 15.2 and 15.2 to 30.5-meter) individual passbands.

(b) Frequency response limitations of the Surface Dynamics Profilometer caused significant differences in the 200 to 400-foot (61.0 to 121.9-meter) passband.

(c) While no significant differences were indicated for the remaining passbands, significant interaction of the pavement section and the profilometer type was present for the 4 to 10, 10 to 25 and 100 to 200-foot (1.2 to 3.1, 3.1 to 7.6 and 30.5 to 61.0-meter) passbands. This means that the differences are dependent on the types of roughness encountered.

(d) For the broad passband of 3 to 200 feet (.9 to 61.0 meters), differences of the means were not significant; however, significant interaction was present. It appears that for the higher amplitude roughness, the Air Force Profilometer measures greater amplitudes than the Surface Dynamics Profilometer, while for lower amplitudes roughness the opposite relationship holds.

(e) Except where significant differences existed between the means, the Air Force Profilometer mean amplitudes were always greater than the surface dynamics mean amplitudes for measurements along the centerline of Runway 17 Right.

(f) Differences between means of Serviceability Indices determined from each profilometer were no greater than 0.1, the standard deviation of serviceability ratings for a sufficiently large rating panel.

(3) Statistically significant differences between profilometers were indicated for the flexible pavement sections measured in this study. It is believed these differences were primarily caused by error in the lateral location of the survey lines measured by the profilometers, resulting in comparison of different lines of survey.

The above summarized results and observations of the comparison experiment lead to several general conclusions concerning the equivalence of the two profilometers.

(1) Although no conclusions can be drawn concerning use of the profilometers on flexible pavements, rigid pavement results indicate that:

(a) given proper lateral control of following wheel location, either profilometer can be used to determine serviceability indices for rigid pavement sections;

(b) even though no definite conclusions can be drawn concerning use of the Surface Dynamics Profilometer for present airfield pavement applications, it is reasonable to assume that similar outputs from an aircraft response simulation for surface

dynamics profiles could be achieved with an increase in operating speed to improve the low frequency response; and

(c) with greater long wavelength response the Surface Dynamics Profilometer, as well as the Air Force Profilometer, could be used with some mathematical model developed in the future to determine airfield pavement serviceability indices.

(2) Due to the greater variation of flexible pavement profiles with respect to lateral location, e.g. rutting in one profilometer's survey line and not the other's, it is believed that improved results, possibly even insignificant differences, could be obtained with improved control of the paths followed by each profilometer on flexible pavement sections.

(3) The profilometers do not differ significantly when considering

(a) ease of operation,

(b) time required for surveying,

(c) system frequency response, or

(d) handling system output.

Recommendations

In this section, areas are discussed in which the comparison of the profilometers could be extended or improved, and some additional comments on how the profilometer systems themselves could be improved.

(1) The results of this comparison could be extended to flexible pavements if measurements were again taken with each profilometer on a flexible pavement section. With improved control of lateral profilometer positions, more definite conclusions could be drawn concerning the comparability of the two profilometers.

(2) The conditional conclusion of profilometer equivalence for rigid highway pavement applications could be extended to airfields if results of aircraft response simulations for each profilometer indicated no significant differences. The Surface Dynamics Profilometer would have to be operated at greater speeds than in this comparison in order to obtain accurate long wavelength information. It is even possible that with additional filtering introduced in a simulation (i.e. landing gear suspension, aerodynamic lift, etc.), that the aircraft responses from the profiles obtained for this comparison might prove to be similar.

(3) Development of a mathematical model to determine airfield serviceability index values, as discussed in Appendix 4, would, provide another means with which to compare the two profilometers.

(4) Either in conjunction with additional comparison on flexible pavements or as a separate experiment, it would be worthwhile to verify the accuracy and precision of the Surface Dynamics Profilometer. Such a verification could be accomplished by comparison of surface dynamics profiles with a true profile such as might be determined by the Air Force's laser profilometer or rod-and-level data.

(5) As discussed in Chapters 2 and 3, both the Air Force and Surface Dynamics Profilometers are effective and efficient systems. There are however improvements that could be made. The Air Force Profilometer could be improved by

(a) automating the raising and lowering of the following wheel

(b) installing a photocell sensing device for more accurate initiation and termination of profile data gathering.

As concerns the Surface Dynamics Profilometer, and considering its age, improvement might be possible by updating or overhauling the components and/or the vehicle itself. Consideration should also be given to the separation of steering and speed control responsibilities.

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APPENDIX 1

PROGRAM ROKRUN FOR CHARACTERIZATION OF PAVEMENT PROFILES

```
CCC*******************************************************************
C
C
C
C                          R O K R U N
C
C                        - VERSION 1.2 -
C
C
C                PROGRAM WHICH ANALYSES PVMT PROFILE
C                DATA TO OBTAIN ROUGHNESS MEASURES.
C
C
C                     WRITTEN - MARCH 1974
C
C                            -BY-
C                     HUGH J. WILLIAMSON
C                 CENTER FOR HIGHWAY RESEARCH
C                UNIVERSITY OF TEXAS AT AUSTIN
C
C                     ADAPTED - JUNE 1975
C
C                            -BY-
C                       CHRIS E. DOEPKE
C              FROM ROKYRD VERSION 2.0 - JAN 1975
C
C                LATEST REVISION - 6 OCTOBER 1975
C
C
C*********************************************************************
C
C  THIS IS AN EXECUTIVE ROUTINE FOR A SET OF SUBROUTINES USED TO
C  CHARACTERIZE A PVMT PROFILE.  DIFFERENCES BETWEEN THE OUTPUTS OF
C  SUCCESSIVE LOW-PASS FILTERS ARE USED TO ISOLATE IRREGULARITIES IN
C  CONTIGUOUS PASSBANDS.  THEN A SET OF MOVING MEAN SQUARE VALUES
C  CORRESPONDING TO EACH PASSBAND IS COMPUTED.  THE MEAN, STANDARD
C  DEVIATION, APPROXIMATING DISCRETE PROBABILITY DENSITY AND
C  DISTRIBUTION FUNCTIONS, AND THE 50, 75, 90, 95, AND 99TH PERCENTILE
C  POINTS ARE COMPUTED FOR EACH SET.  CALCULATIONS ARE PERFORMED FOR
C  THE RIGHT AND LEFT PROFILES AND FOR THE POINTWISE DIFFERENCE BETWEEN
C  THE TWO PROFILES.  HIGHWAY PAVEMENT SI VALUES CAN ALSO BE COM-
C  PUTED (BASED ON ROUGHNESS MEASURES) FOR THE PASSBANDS: 4 TO 10 FT,
C  10 TO 25 FT, 25 TO 50 FT, 50 TO  100 FT, AND AN OVERALL SI, IF THE
C  ABOVE PASSBANDS ARE AMOUNG THOSE SPECIFIED.
C
C*********************************************************************
C
C
C          DATA DECKS FOR SUCCESSIVE CASES CANNOT BE STACKED.
C
C                   THE INPUTS ARE AS FOLLOWS:
C                   --- ------ --- -- -------
C
C                           FIRST CARD
C                           ----- ----
C                           TITLE CARD
C                          FORMAT(7A10,A2)
C
C  TI        72-CHARACTER TITLE PRINTED ON EACH PAGE OF OUTPUT AND PLOT.
C
C
C                             SECOND CARD
C                             ------ ----
C
C                   CHARACTERISTICS OF PROFILE DATA
C                        FORMAT(2I5,4F10.0,I5)
C
C  IFILE     NO. OF FILE ON TAPE.  IF LE 0, IFILE WILL BE SET EQUAL TO 1
C            THE FILE NUMBERS FOR SUCCESSIVE CASES MUST BE NONDECREASING
C  NREC      NO. OF FIRST LOGICAL RECORD ON TAPE TO READ.  IF EQ
C            0, NREC WILL BE SET TO 1.
C            IF LT 0, DATA WILL BE READ FROM CARDS, NOT TAPE.
C            (SEE SUBROUTINE RDPROF.)
C            IT IS ASSUMED THAT THERE ARE 750 PAIRS OF POINTS PER
C            RECORD.
C            (SEE SUBROUTINE RDPROF.)
C  GAINR,    FACTORS USED TO CONVERT THE INPUT PROFILES TO
C  GAINL     INCHES.  THIS IS DONE IN SUBROUTINE RDPROF.
C  STEPIN    STEP SIZE OF INDEPENDENT VARIABLE IN THE ARRAYS ON TAPE
C            OR CARDS (FT.).  IF LE 0, WILL BE SET EQUAL TO .169=1/5.92,
C            WHICH IS THE STANDARD VALUE FOR DIGITIZED PROFILOMETER DATA
C            THE INPUT RECORD WILL BE SUBSAMPLED BY THE RATIO
C            T/STEPIN, WHICH SHOULD BE AN INTEGER.  IF NOT, T WILL
C            BE ROUNDED SO THAT THE RATIO IS AN INTEGER.
C            N IS THE NUMBER OF POINTS AFTER SUBSAMPLING.
C            (NOTE : STEPIN MUST BE THE STEPSIZE USED IN THE
C            DIGITIZATION OF THE DATA.)
C  STRT      STARTING DISTANCE OF SECTION FOR PLOT PURPOSES.
C            THE FIRST VALUE PLOTTED ON THE X-AXIS WILL BE
C            *STRT *.  REMEMBER EACH PLOT STARTS *SKB* FEET AFTER
C            THE START OF EACH SECTION.
C  IFILT     CHOICE OF FILTER. IF IFILT = 1, A FOUR POLE SINE-BUTTER-
C            WORTH DIGITAL FILTER IS USED AS PROVIDED BY THE AIR FORCE
C            WEAPONS LAB. DEFAULT VALUE OF ZERO WILL CAUSE USE OF
C            THE NORMAL ROKYRD FILTER. *IFILT* SHOULD BE G.T. 1 IF
C            IT IS DESIRED TO USE THE SAME FILTER AS IN PREVIOUS CASES.
C
C                             THIRD CARD
C                             ----- ----
C
C           PARAMETERS SPECIFYING PROCESSING TO BE PERFORMED
C                  FORMAT(4F10.0,4I5,A3,2X,A5,A4)
C
C  DIST      LENGTH IN FEET OF SECTION OF INTEREST FOR RMS CALCULATIONS
C            AND PLOTS.
C            ( BY DEFAULT DIST WILL BE SET TO A VALUE WHICH WILL ALLOW
C              NINE FULL RECORDS TO BE READ WITH SKB AND SKA SET TO
C              WAVEL(NF).)
C  SKB       DISTANCE IN FEET FROM BEGINNING OF DATA RECORD TO BEGINNING
C            OF SECTION OF INTEREST.  THIS SHOULD BE AT LEAST ONE WAVE-
C            LENGTH AT THE LOWEST FREQUENCY TO ALLOW TRANSIENT EFFECTS
C            TO DIE OUT.
C            ( IF DIST .LE. 0, SKB WILL BE SET TO WAVEL(NF) )
C  SKA       LENGTH IN FEET TO BE READ IN AFTER SECTION OF INTEREST TO
C            ALLOW TRANSIENT EFFECTS TO DIE OUT ON THAT END. SHOULD BE
C            AT LEAST WAVEL(NF).
C            ( IF DIST .LE. 0, SKA WILL BE SET TO WAVEL(NF) )
C  T         STEP SIZE OF INDEPENDENT VARIABLE. DISTANCE ALONG THE PAVE-
C            MENT IN FEET.
C            ( BY DEFAULT T WILL BE SET TO THE VALUE OF STEPIN )
C  NF        NO. OF WAVELENGTHS DEFINING THE FILTER PASSBANDS.
C            1 LE NF LE 10.
C            NF SHOULD BE NEGATIVE THE NUMBER OF WAVELENGTHS IF IT IS
```

```
C               DESIRED TO USE THE SAME SET OF FILTERS AS IN THE PREVIOUS
C               CASE, I.E., IF IT IS NOT NECESSARY TO COMPUTE THE
C               COEFFICIENTS.
C               (DEFAULT VALUE IS 5)
C     NP        AFTER LOW-PASS FILTERING WITH CUTOFF FREQ. 1/WAVEL(1),
C               THE SAMPLING RATE FOR SUBSEQUENT FILTERING WILL BE
C               DECREASED BY A FACTOR OF NP.  DEFAULT VALUE = 2.
C     IGAIN     NO. OF POINTS IN THE GAIN VS. FREQUENCY FNS. IF IGAIN
C               LE 0 OR GE 101, IGAIN WILL BE SET TO 100.
C     IPDF      NO. OF POINTS FOR THE DISCRETE P.D.F. AND C.D.F.
C               IF IPDF EQ 0 OR GE 101, IPDF WILL BE SET TO 100.
C               IF IPDF LT 0 , THEN IPDF WILL BE SET TO -IPDF ,
C               AND THE PDF AND THE CDF TABLES WILL BE PRINTED .
C               (THE SUMMARY TABLE WILL BE PRINTED IN EITHER CASE)
C     INK       IF *INK* APPEARS IN COLUMNS 61 - 63 OF THE CARD, THEN
C               ANY PLOTS PRODUCED WILL BE IN INK.  OTHERWISE BALL-
C               POINT PLOTS WILL BE MADE.  (INK PLOTS SHOULD BE USED
C               FOR ALL OUTPUT WHICH IS TO BE PUT IN A REPORT.)
C     IPUNCH    IF *PUNCH* APPEARS IN COLUMNS 66 - 70 OF THE CARD, THEN
C               VARIABLES TO BE USED IN THE REGRESSION MODEL WILL BE
C               PUNCHED ONTO CARDS.  (THE USER MUST INCLUDE A PUNCH
C               LIMIT ON HIS JOB CARD IF THIS OPTION IS SELECTED.)
C     ITYPE     DENOTES THE TYPE OF PAVEMENT THIS ROAD SECTION IS
C               CONSTRUCTED OF .THE TYPES ARE :
C                *HMAC* , *ST  * , *OVLY* , *CRCP* , *JRCP* .
C               ONE OF THESE TYPES SHOULD APPEAR IN COLUMNS 71 - 74
C               OF THIS CARD .
C               ( DEFAULT VALUE IS JRCP )
C
C                               FOURTH CARD
C                               ------ ----
C               WAVELENGTHS AT WHICH PASSBANDS ARE TO CUT OFF
C                               FORMAT(8F10.0)
C
C     WAVEL     ARRAY OF NF WAVELENGTHS (FT.).  WAVEL(I) LT WAVEL(I+1).
C               THE NF PASSBANDS FOR THE FINAL OUTPUT ARE AS FOLLOWS
C               LAMBDA LT WAVEL(1).
C               WAVEL(I) LT LAMBDA LT WAVEL(I+1), 1 LE I LT NF.
C               IF NF .LT. 0, INDICATING THAT THE COEFFICIENTS OF THE
C               FILTER WILL BE THOSE USED IN THE PREVIOUS PROBLEM, THEN
C               THE SAME WAVELENGTHS WILL HAVE TO BE USED.  HENCE THIS
C               CARD MUST BE OMITTED AND THE PLOTTING OPTIONS CARD MUST
C               IMMEDIATELY FOLLOW THE THIRD CARD.
C               IF NF = 9 OR NF = 10, TWO CARDS WILL BE NEEDED FOR THE
C               WAVELENGTHS.  THIS MEANS THAT THE PLOTTING OPTIONS CARD
C               WILL BE THE SIXTH RATHER THAN THE FIFTH CARD.
C     ****  SPECIAL NOTE  ****
C               IF THE AFWL FILTER HAS BEEN CHOSEN (IFILT G.T. 1), THE
C               ARRAY *WAVEL* BECOMES THE INPUT WAVELENGTHS AS FOLLOW:
C     WAVEL(1)  BAND PASS FILTER  SHORT WAVELENGTH (BEGINNING)
C     WAVEL(2)  BAND PASS FILTER  LONG WAVELENGTH (END OF BAND)
C     WAVEL(3)  LOW PASS FILTER   CUT OFF WAVELENGTH
C     WAVEL(4)  HIGH PASS FILTER  BEGINNING WAVELENGTH
C     WAVEL(5)  ORDER OF BAND PASS FILTER  (FLOATING POINT)
C     WAVEL(6)  ORDER OF LOW PASS FILTER   (FLOATING POINT)
C     WAVEL(7)  ORDER OF HIGH PASS FILTER  (FLOATING POINT)
C     WAVEL(8)  BAND STOP FILTER  SHORT WAVELENGTH
C     WAVEL(9)  BAND STOP FILTER  LONG WAVELENGTH
C     WAVEL(10) ORDER OF BAND STOP FILTER  (FLOATING POINT)
C     ********
```

```
C
C                               FIFTH CARD
C                               ----- ----
C                            PLOTTING OPTIONS
C                          FORMAT(19I1,1X,11F5.0)
C
C     THE FIRST 19 VALUES ARE ALL READ IN I1 FORMAT STARTING IN COL. 1.
C     SET =1 IF PLOT IS DESIRED, =0 (OR LEAVE BLANK ON DATA CARD) IF NOT.
C
C     IFP(1)    REDUCE ALL PLOTS BY A FACTOR OF 0.8 FOR REPORTS.
C     IFP(2)    PLOT ONLY FILTERED PROFILES.
C     IFP(3)    PLOT ONLY UNFILTERED PROFILES.
C
C     THE P.D.F. PLOT, C.D.F. PLOT, AND PLOT OF UNFILTERED AND FILTERED
C     PROFILES ARE DONE SUBJECT TO THE FOLLOWING OPTIONS.
C     ALL PERTINENT OPTIONS MUST BE SPECIFIED FOR A PARTICULAR PLOT TO BE
C     MADE.  E.G., IF THE RIGHT OPTION AND THE C.D.F. OPTION ARE SPECIFIED,
C     BUT THE FIRST PASSBAND OPTION IS NOT, THEN THE C.D.F. FOR PASSBAND 1
C     FOR THE RIGHT PROFILE WILL NOT BE PLOTTED.
C     WARNING - IF ALL OPTIONS ARE SELECTED, THE NUMBER OF PLOTS WILL BE
C     LARGE.
C     IFP(4)    RIGHT.
C     IFP(5)    LEFT.
C     IFP(6)    DIFFERENCE.
C     IFP(7)    C.D.F.
C               (THIS OPTION HAS NOT BEEN IMPLEMENTED YET)
C     IFP(8)    P.D.F.
C               (THIS OPTION HAS NOT BEEN IMPLEMENTED YET)
C     IFP(9)    FILTERED AND UNFILTERED PROFILES ON THE SAME PLOT.
C     IFP(9+I)  ITH PASSBAND.  THE INDEX INCREASES AS THE WAVELENGTH
C               INCREASES.  E.G., LAMBDA LT WAVEL(1) IS THE FIRST PASSBAND.
C     XAXL       LENGTH OF X-AXIS. DEFAULT VALUE (ZERO) PROVIDES A ROUTINE
C               FOR DETERMINING A CONVENIENT SCALE.
C     YSCAL(I)  ACTUAL PLOTTING PARAMETERS USED TO FORCE THE SCALE
C               OF THE Y AXIS, YSCAL(1) = NO.OF UNITS PER INCH OF
C               PLOT FOR THE Y AXIS (PASSBAND - WAVEL(1) TO WAVEL(2).
C
C                              TAPE OR CARDS
C                              ---- -- -----
C                              PROFILE DATA
C     X         SUCCESSIVELY, THE RIGHT AND LEFT PROFILE ARRAYS. (IN.)
C               THE TAPE OR CARDS ARE READ IN SUBROUTINE *RDPROF*.
C               THIS DATA IS READ IN AS  RIGHT AND LEFT
C               WHEELPATH POINTS, THE DIFFERENCE IS COMPUTED, AND
C               THEN EACH OF THE THREE SERIES IS STORED SEPARATELY
C               ON A SCRATCH FILE (TAPE2) WHERE IT CAN BE ACCESSED
C               WHEN NEEDED FOR PROCESSING.
C
C     THE INPUT TO EACH LOW-PASS FILTER AFTER THE FIRST IS THE DECIMATED
C     OUTPUT FROM THE FIRST.
C     IT WOULD BE POSSIBLE AT EACH STEP TO DECIMATE THE OUTPUT OF THE
C     PREVIOUS LOW-PASS FILTER TO OBTAIN THE INPUT FOR THE NEXT FILTER,
C     BUT THEN THE FINAL OUTPUT WOULD HAVE BEEN FILTERED NF TIMES, WHICH
C     IS CONSIDERED UNDESIRABLE, SINCE SOME DISTORTION IS INTRODUCED BY
C     EACH FILTER.
C
C***********************************************************************
C
```

```
      PROGRAM ROKRUN(INPUT=1000,OUTPUT,TAPE1,TAPE2,TAPE5=INPUT,TAPE6,
     1PUNCH)
      DIMENSION XUP(4000),XF(4000),XLOW(4000)
      DIMENSION FPRAM(6),NPRAM(4)
      COMMON /COEF/ A(7,10), B(7,10)
      COMMON /DIRECT/ FSTEP, IGAIN, NF, NSEC, NSECN, T, TI(8),
     1                TNP, WAVEL(10) ,YSCAL(10) , XAXL , STRT
      COMMON /CDFPDF/ DX, IPDF, CDF(100), PDF(100), FREQ(10),
     1                PCT(5), NPTS, STEPIN, NP
      COMMON /INICAL/ IFILE, IFP(19), IPDFLG, IPUNCH, IRATIO, N, NBGN,
     1                NEWN, NPNZRO, NREC, NSKB, NSKBN, STD, U
      COMMON X(8000),XOUT(8000),Z(8000)
C
C         PRESET STORAGE, PRINT TITLE PAGE.
      CALL PRS
C
C         READ DIRECTIVE INPUT.
 1000 CALL RDI (IFCOEF,ITYPE,IFILT)
C
C         IF NECESSARY, COMPUTE THE COEFFICIENTS FOR THE FILTERS.
      IF (IFCOEF.NE.0.AND.IFILT.LT.1) CALL CCF
C
C         CALL ROUTINE TO READ DATA FROM TAPE OR CARDS.
      CALL RDPROF(ITYPE)
C
C       THE THREE PASSES THROUGH THE FOLLOWING LOOP ARE MADE TO PERFORM
C       CALCULATIONS FOR THE RIGHT, LEFT, AND RIGHT MINUS LEFT PROFILES
      DO 500 IPROF=1,3
C
C     READ THE PROPER SERIES OF DATA PTS INTO ARRAY <X> FOR PROCESSING
C     BY THE FILTERING ROUTINES.  A TOTAL OF <N> PTS ARE COPIED, AND
C     THE LAST POINT IS EXTENDED <NPNZRO> EXTRA WORDS TO ALLOW TRANSIENT
C     EFFECTS TO DIE OUT IN THE FORWARD FILTER AND TO PREVENT A
C     DISCONTINUITY FROM OCCURRING AT THE END OF THE SAMPLE.
C     THE DATA IS STORED ON A SCRATCH FILE (TAPE2) WHICH IS ASSUMED TO
C     BE POSITIONED AT THE BEGINNING OF A RECORD CONTAINING SERIES
C     <IPROF>.
      READ (2) (X(J),J=1,N)
C
C         IF THE APML DIGITAL FILTER IS NOT TO BE USED, DO NOT
C         CONVERT WAVELENGTHS TO FREQUENCIES.
      IF(IFILT.LE.0) GO TO 4
      FPRAM(1)=86./(3.*WAVEL(3))
      FPRAM(2)=86./(3.*WAVEL(9))
      FPRAM(3)=86./(3.*WAVEL(1))
      FPRAM(4)=86./(3.*WAVEL(4))
      FPRAM(5)=86./(3.*WAVEL(2))
      FPRAM(6)=86./(3.*WAVEL(8))
      NPRAM(1)=WAVEL(6)
      NPRAM(2)=WAVEL(7)
      NPRAM(3)=WAVEL(10)
      NPRAM(4)=WAVEL(5)
      CALL PREFILT(X,N,IFILT,NPNZRO,XOUT,FPRAM,NPRAM)
      NPTS=N
      GO TO 9
    4 CONTINUE
            N1 = N + 1
      DO 5 J = N1, NPNZRO
    5       X(J) = X(N)
C
C         PERFORM CALCULATIONS FOR THE PASSBAND LAMBDA LT WAVEL(1).
      CALL FILTER(X,NPNZRO,A(1,1),A(2,1),B(1,1),XOUT,Z)
C
C     NOW DECIMATE THE LOW-PASS FILTERED OUTPUT - IN ALL SUBSEQUENT
C     FILTERING BY *FILTER* , THE PASSBANDS WILL BE CONTAINED IN THE
C     PASSBAND OF THE FIRST LOW-PASS FILTER.
C      (XF)  = DECIMATED PROFILE
C      (NE2) = NO. OF PTS. IN XF, INCLUDING WAVELENGTH EXTENSION
                NE2 = 0
      DO 10 I = NBGN, NPNZRO, NP
                NE2 = NE2 + 1
                XF(NE2) = XOUT(I)
                XUP(NE2) = XOUT(I)
   10 CONTINUE
         IF (NE2 .GT. 4000)  GO TO 17
C
C     NOTE THAT NEWN IS THE NUMBER OF POINTS AFTER DECIMATION.  TNP IS
C     THE NEW STEP SIZE.
C     SUBTRACT THE LOW-PASS FILTERED OUTPUT FROM THE PROFILE TO OBTAIN
C     A HIGH-PASS FILTERED PROFILE.
      DO 8 I=1,N
    8 XOUT(I)=X(I)-XOUT(I)
      NPTS=WAVEL(1)/T+.5
    9 CALL MOVESQ(XOUT(NSKB),NSEC,NPTS,Z,NZ)
      CALL DISPDF(Z,NZ,IPDF,PDF,CDF,DX,U,STD)
C
C         NOW CALL SUBROUTINE TO COMPUTE PERCENTILE POINTS.
      CALL PCTILE(CDF,IPDF,DX,PCT)
C
C         CALL SUBROUTINE TO DISPLAY RESULTS.
      CALL DISPLY (1, IPROF, X(NSKB), XOUT(NSKB))
C
C         NOW PERFORM CALCULATIONS FOR THE OTHER PASSBANDS.
      IF(NF.LE.1)GO TO 500
      IF(FILT.EQ.1) GO TO 500
      DO 50 J=2,NF
      CALL FILTER(XF,NE2,A(1,J),A(2,J),B(1,J),XLOW,Z)
C        THE DIFFERENCE BETWEEN TWO LOW-PASS FILTERED TIME SERIES IS,
C        EFFECTIVELY, A BANDPASS-FILTERED TIME SERIES.
      DO 12 I=1,NEWN
   12 XOUT(I)=XUP(I)-XLOW(I)
      NPTS=WAVEL(J)/TNP+.5
      CALL MOVESQ(XOUT(NSKBN),NSECN,NPTS,Z,NZ)
      CALL DISPDF(Z,NZ,IPDF,PDF,CDF,DX,U,STD)
      CALL PCTILE(CDF,IPDF,DX,PCT)
      CALL DISPLY ( J, IPROF, X(NSKB), XOUT(NSKBN) )
      IF(J.EQ.NF) GO TO 50
      DO 15 I=1,NEWN
   15 XUP(I)=XLOW(I)
   50 CONTINUE
  500 CONTINUE
C        PRINT SUMMARY STATISTICS FOR ENTIRE PROBLEM.
      CALL PSS (ITYPE)
      GO TO 1000
C       ERROR MESSAGE
   17 PRINT 2000, NE2
 2000 FORMAT (*0TOTAL NUMBER OF PTS. AFTER DECIMATION IS:*,I10,
     +  /,X,*( NP IS TOO SMALL )*)
      CALL ABNORML
      END
```

```
      SUBROUTINE PRS
CC
C     PRS - PRESET STORAGE, PRINT TITLE PAGE.
C
      COMMON /HDG/ HEADER(5), NPAGE
      COMMON /PLOTS/ ISRS(2,3),NFILE,SCL(4),Y1,YD,NPU(3),NPF(3)
      DATA ISRS / 10H    RIGHT ,10HPROFILE   ,
     1            10H    LEFT P,10HROFILE    ,
     2            10H    DIFF. ,10HPROFILE   /
      DATA NPAGE / 1 /
      REWIND 1
      CALL DATE (IDAY)
      ENCODE ( 43, 1, HEADER )  IDAY
    1 FORMAT (*ROKRUN  -  VER. 1.1  - *A10*  -  PAGE *)
      PRINT 2, HEADER, NPAGE
    2 FORMAT (1H1,32X,4A10,A3,I3,20(/),36X,*R O K R U N*/)
      PRINT 3
    3 FORMAT (34X,*- VERSION 1.2 -*//)
      PRINT 4
    4 FORMAT (24X,*PROGRAM WHICH ANALYSES PVMT PROFILE*/24X,*DATA *
     *  *TO OBTAIN ROUGHNESS MEASURES.*///31X,*WRITTEN - MARCH 1974*
     *  //39X,*-BY-*/32X,*HUGH J. WILLIAMSON*/28X,*CENTER FOR HIGH*
     *  *WAY RESEARCH*/27X,*UNIVERSITY OF TEXAS AT AUSTIN*/)
      PRINT 6
    6 FORMAT(//31X,*ADAPTED - JUNE 1975*//39X,*-BY-*/39X,
     2*CHRIS E. DOEPKE*/25X,*FROM ROKYRD VERSION 2.0 - JAN 75*)
      PRINT 5
    5 FORMAT (25X,*LATEST REVISION - 6 OCTOBER 1975*)
         RETURN
      END
```

```
      SUBROUTINE RDI (IFCOEF,ITYPE,IFILT)
CC
C     RDI - READ DIRECTIVE INPUT
C
      COMMON /GAIN/ GAINR, GAINL
      COMMON /DIRECT/ FSTEP, IGAIN, NF, NSEC, NSECN, T, TI(8),
     1                TNP, WAVEL(10) ,YSCAL(10) , XAXL , STRT
      COMMON /CDFPDF/ DX, IPDF, CDF(100), PDF(100), FREQ(10),
     1                PCT(5), NPTS, STEPIN, NP
      COMMON /INICAL/ IFILE, IFP(19), IPDFLG, IPUNCH, IRATIO, N, NBGN,
     1                NEWN, NPNZRO, NREC, NSKB, NSKBN, STD, U
      COMMON /HDG/ HEADER(5), NPAGE
      COMMON /DI/ INK, SKB, DIST, SKA, TOT, USKB, UDIST, USKA, UTOT
      DIMENSION STR(2), STS(2), ENS(2), END(2)
      DATA STR / 10H  START OF, 7H RECORD    /,
     +     STS / 10H  START OF, 8H SECTION   /,
     +     ENS / 10H    END OF , 7HSECTION    /,
     +     END / 10HEND OF DAT, 9HA READ IN  /
C
C     READ TITLE CARD.
C
      READ 30,TI
   30 FORMAT(8A10)
      IF (EOF,5) 42,44
   42 CALL EXIT
C
C     READ IN THE CHARACTERISTICS OF THE DATA.
C
   44 READ 1, IFILE, NREC, GAINR, GAINL, STEPIN, STRT, FILT
    1 FORMAT (2I5,3F10.0,I5,F10.0)
C
C     READ IN PARAMETERS SPECIFYING PROCESSING TO BE PERFORMED ON THE
C     DATA.
C
      READ 3,DIST, SKB, SKA, T, NFN, NP, IGAIN, IPDF, INK, IPUNCH, ITYPE
    3 FORMAT (4F10.0,4I5,A3,2X,A5,A4)
C
C     CHECK VALUE OF <NF>, SET FLAG <IFCOEF> TO 0 IF COEFFICIENTS NEED
C     NOT BE RECOMPUTED.
C
      IFCOEF = 0
      IF (NFN .LT. 0)  GO TO 39
      IF (NFN .EQ. 0)  NFN = 5
      NF = NFN
      IFCOEF = 1
      IF(0.GT.NF .OR. NF.GT.10) GO TO 40
C
C     READ IN THE WAVELENGTHS AT WHICH THE PASSBANDS CUT OFF.
C
      READ 28,(WAVEL(I),I=1,NF)
   28 FORMAT(8E10.4)
C
C     READ CARD CONTAINING PLOT OPTIONS.
C
   39 READ 34, (IFP(J),J=1,19),XAXL,(YSCAL(J),J=1,10)
   34 FORMAT (19I1,1X,11F5.0)
C
C     PRINT HEADING FOR PAGE SHOWING INPUTS.
C
      NPAGE = NPAGE + 1
```

```
      PRINT 31, HEADER, NPAGE, TI
   31 FORMAT (1H1,32X,4A10,A3,I3,4(/),8X,8A10,///,29X,*D I R E *
     + *C T I V E   I N P U T*,//,26X,*DISTANCE*,23X,*SPECIFIED*,5X,
     + *ROUNDED*,/,16X,*FROM*,21X,*TO*,16X,*VALUE*,6X,*VALUE USED*)
C
C     CHECK FOR ERRORS, MAKE DEFAULT SETTINGS, PRESET DERIVED VALUES.
C
      CALL PDI (ITYPE)
C
C     PRINT DIRECTIVE PARAMETERS.
C
      PRINT 32, STR, STS, SKB, USKB, STS, ENS, DIST, UDIST, ENS, END,
     +             SKA, USKA, STR, END, TOT, UTOT
   32 FORMAT (8X,2A10,4X,2A10,2(4X,F10,2))
      IF (IPUNCH ,EQ, 5HPUNCH)  PRINT 37
   37 FORMAT (//,22X,*OPTION TO PUNCH REGRESSION DATA ON CARDS *
     +  *SELECTED,*)
      PRINT 2,N,NF,NP,IGAIN,IPDF,IFILE,NREC,T,STEPIN,GAINR,GAINL,ITYPE,
     1           (WAVEL(I),I=1,NF)
    2 FORMAT(//4X,*N*5X,*NF*4X,*NP IGAIN  IPDF  IFILE  NREC*7X,*T*,13X,
     1*STEPIN*10X,*GAINR*11X,*GAINL*12X,*ITYPE*/,7(1X,I5),4(1X,E15.6),
     28X,A4,//,(* WAVELENGTHS*,6E15,6))
      PRINT 35,INK,(IFP(J),J=1,19),XAXL,(YSCAL(J),J=1,10)
   35 FORMAT(*0PLOT OPTIONS : *A3,19I2,/,11F6,2)
      PRINT 36, NSEC, NSKB, NSECN, NSKBN, NBGN, NEWN
   36 FORMAT(//6X,*NSEC*8X,*NSKB*6X,*NSECN*6X,*NSKBN*7X,*NBGN*7X,
     1*NEWN*,/,6(1X,I10)//)
      RETURN
C
C        ERROR MESSAGE
   40 PRINT 27,NF
   27 FORMAT(*0ERROR, NF=*,I5)
      CALL ABNORML
      END
```

```
      SUBROUTINE PDI (ITYPE)
CC
C     PDI - PROCESS DIRECTIVE INPUT: MAKE DEFAULT SETTINGS, CHECK FOR
C                                    ERRORS, COMPUTE DERIVED VALUES.
C
      COMMON /PLOTS/ ISRS(2,3),NFILE,SCL(4),Y1,YD,NPU(3),NPF(3)
      COMMON /DIRECT/ FSTEP, IGAIN, NF, NSEC, NSECN, T, TI(8),
     1                TNP, WAVEL(10) ,YSCAL(10) , XAXL , STRT
      COMMON /CDFPDF/ DX, IPDF, CDF(100), PDF(100), FREQ(10),
     1                PCT(5), NPTS, STEPIN, NP
      COMMON /INICAL/ IFILE, IFP(19), IPDFLG, IPUNCH, IRATIO, N, NBGN,
     1                NEWN, NPNZRO, NREC, NSKB, NSKBN, STD, U
      COMMON /DI/ INK, SKB, DIST, SKA, TOT, USKB, UDIST, USKA, UTOT
      DATA TPI / 6.283185308 /
C *** NOT TRANSPORTABLE **********************
      NFILE = 4LPLOT
      IF (INK ,EQ, 3HINK)  NFILE = 5LPLOTI
C ******************************************
      DO 2 I=1,NP
    2 FREQ(I) = 1,0 / WAVEL(I)
      IF(IFILE,LE,0) IFILE=1
      IF(NREC,EQ,0) NREC=1
      IF(NP,LT,1) NP=2
      IF(IGAIN,LE,0 ,OR,IGAIN,GT,100) IGAIN=100
      IPDFLG = 0
      IF (IPDF ,GE, 0)  GO TO 31
      IPDFLG = 1
      IPDF = -IPDF
   31 IF(IPDF,EQ,0 ,OR, IPDF,GT,100) IPDF=100
      IF(STEPIN,LE,0.) STEPIN=,169
      IF(T,LE,0) T=STEPIN
      IRATIO=T/STEPIN+,5
      IF(IRATIO,LT,1) IRATIO=1
      TT=STEPIN*IRATIO
      IF(ITYPE,EQ,4H    ) ITYPE = 4HJRCP
C
C        IRATIO IS THE RATE AT WHICH TO SUBSAMPLE THE PROFILE ON TAPE OR
C        CARDS,  I.E., USE THE 1ST, (1+IRATIO)TH, (1+2*IRATIO)TH, . . .
C        POINTS.
      IF(ABS(T-TT).LT.1.E-6*T) GO TO 32
      PRINT 99,T,TT
   99 FORMAT(*0CHANGE T FROM*,E15.6,* TO*,E15.6,*TO MAKE DECIMATION RATI
     1O AN INTEGER*)
      T=TT
   32 DO 3 I=2,NF
    3 IF(WAVEL(I-1).GE.WAVEL(I)) GO TO 33
      TNP = T * NP
      FSTEP = TPI*1.25 / (WAVEL(1)*IGAIN)
C
C        COMPUTE NO. OF PTS. BEFORE AND WITHIN SECTION WHICH IS OF
C        INTEREST, AND TOTAL NO. OF PTS. TO BE READ (UNFILTERED PRO-
C        FILE).
C        <NSKB> : INDEX OF FIRST PT. IN SECTION OF INTEREST.
C        <NSEC> : NO. OF PTS. IN SECTION.
C        <N>    : TOTAL NO. OF PTS. TO BE READ FROM TAPE FOR EACH
C                 WHEELPATH, WITH STEP SIZE <T> (I.E.: DECIMATED IF
C                 NECESSARY).
      IF (DIST .GT. 0.0)  GO TO 100
      DIST = -DIST
      SKB = WAVEL(NF)
```

```
      SKA = SKB
      IF (DIST .NE. 0.0)  GO TO 100
      DIST = AMIN1 (1140.581 - SKB - SKA - T, 7499 * T - 3 * WAVEL(NF) )
C
C         CHECK FOR INSUFFICIENT SAMPLE LENGTH.
      IF (DIST .LE. T)  GO TO 34
  100 TOT = SKB + DIST + SKA
      N = 1.5 + TOT / T
      NSKB = 1.5 + SKB / T
      NSEC = 1.5 + DIST / T
C
C          COMPUTE NO. OF PTS. OF DECIMATED FILTERED PROFILES.
C          <NBGN> : INDEX OF PT. AT WHICH TO BEGIN DECIMATION IN ORDER
C                   TO BE CERTAIN THAT THE FIRST PT. OF THE SECTION OF
C                   INTEREST REMAINS AFTER DECIMATION IS COMPLETE.
C          <NEWN>,<NSECN>,<NSKBN> : VALUES OF <N>,<NSEC>, AND <NSKB>
C                   RESPECTIVELY AFTER DECIMATION.
      NEWN = (N + NP - 1) / NP
      NSECN = (NSEC + NP - 1) / NP
      NBGN = MOD( NSKB-1, NP ) + 1
      NSKBN = 1 + (NSKB - NBGN) / NP
C
C          COMPUTE ACTUAL DISTANCES CORRESPONDING TO NO. OF PTS. USED.
      UTOT = (N - 1) * T
      USKB = (NSKB - 1) * T
      UDIST = (NSEC - 1) * T
      USKA = UTOT - USKB - UDIST
C
C         ZEROES WILL BE EXTENDED TO THE RIGHT OF THE TIME SERIES TO BE
C         FILTERED TO ALLOW THE TRANSIENTS OF THE FORWARD FILTER TO DIE
C         OUT BEFORE THE BACKWARD FILTER IS DONE (SEE SUBROUTINE FILTER).
C         THE EXTENSION IS ONE CYCLE AT THE LONGEST WAVELENGTH OF INTER-
C         EST, WAVEL(NF).
      NZERO=WAVEL(NF)/T+.5
C
C         CHECK FOR POSSIBLE OVERFLOW OF ARRAY X.
      NPNZRO=N+NZERO
      IF(NPNZRO.LE.8000) RETURN
C
C        ERROR MESSAGES
      PRINT 38,NPNZRO
   38 FORMAT(*0DIMENSIONS WOULD HAVE BEEN EXCEEDED  NPNZRO=*,I10)
      CALL ABNORML
   33 PRINT 4, ( WAVEL(J), J = 1, NF )
    4 FORMAT(*0WAVEL VALUES ARE NOT INCREASING*,/,X,10F10.2)
      CALL ABNORML
   34 PRINT 101, WAVEL(NF), DIST
  101 FORMAT (*0ERROR IN DIRECTIVE INPUT, LONGEST WAVELENGTH IS*F7.1
     +         *, SECTION LENGTH IS*F7.1)
      CALL ABNORML
      END
```

```
      SUBROUTINE CCF
CC
C     CCF - COMPUTE THE COEFFICIENTS FOR THE FILTERS.
C
      DIMENSION G2(100,10)
      COMMON /COEF/ A(7,10), B(7,10)
      COMMON /DIRECT/ FSTEP, IGAIN, NF, NSEC, NSECN, T, TI(8),
     1                TNP, WAVEL(10) ,YSCAL(10) , XAXL , STRT
      COMMON X(8000),XOUT(8000),Z(8000)
      EQUIVALENCE(G2(1,1),Z(1))
      DATA TPI,AA/6.283185308,.70711/
      CALL COEFLW(TPI/WAVEL(1),AA,T,A(1,1),B(1,1),IFLAG,WC)
C
C     BRANCH IF ERROR IN COEFLW.
      I=1
      IF (IFLAG .NE. 2)  GO TO 999
      CALL GAIN2(G2(1,1),IGAIN,WC,FSTEP,T)
      DO 7 I=2,NF
      CALL COEFLW(TPI/WAVEL(I),AA,TNP,A(1,I),B(1,I),IFLAG,WC)
C
C     BRANCH IF ERROR IN COEFLW.
      IF (IFLAG .NE. 2)  GO TO 999
      CALL GAIN2(G2(1,I),IGAIN,WC,FSTEP,TNP)
    7 CONTINUE
C
C         CALL SUBROUTINE TO DISPLAY THE GAINS OF THE LOW-PASS FILTERS.
C              **** HAS NOT BEEN IMPLEMENTED YET. ****
C
C         CONVERT THE LOW-PASS FILTER GAINS TO THE GAINS OF THE EFFECTIVE
C         BAND-PASS FILTERS.
      N1=NF
      N2=NF
   22 N2=N2-1
      DO 21 I=1,IGAIN
   21 G2(I,N1)=G2(I,N2)-G2(I,N1)
      N1=N1-1
      IF(N1.GT.1) GO TO 22
      DO 23 I=1,IGAIN
   23 G2(I,1)=1.-G2(I,1)
C
C         CALL SUBROUTINE TO DISPLAY THE GAINS OF THE BAND-PASS FILTERS.
C              **** HAS NOT BEEN IMPLEMENTED YET. ****
      RETURN
C
C        PRINT ERROR MESSAGE AND ABORT.
  999 PRINT 6,IFLAG,I,WC
    6 FORMAT(*0ERROR IN COEFLW, IFLAG,I,WC=*,2I5,E20.8)
      CALL ABNORML
      END
```

```
      SUBROUTINE RDPROF(ITYPE)
CC
C     SUBROUTINE RDPROF READS IN THE DATA FROM EITHER TAPE OR CARDS,
C   SCALES THE DATA, THEN STORES IT ON A SCRATCH FILE (TAPE2).  THE
C   RIGHT PROFILE IS STORED SEQUENTIALLY AS ONE RECORD.  THE LEFT PRO-
C   FILE IS STORED IN THE NEXT RECORD, AND THE DIFFERENCE (RIGHT -
C   LEFT) IS STORED IN THE RECORD IMMEDIATELY FOLLOWING.
C      <NREC> : RECORD AT WHICH TO BEGIN READING.
C               (IF <NREC> .LT. 0, DATA READ FROM CARDS)
C      <IFILE> : POINTER TO NEW FILE.
C      <LREC> :  CURRENT RECORD POINTER (IT WILL BE UPDATED).
C
C     IF ANY PLOTS OF FILTERED OR UNFILTERED PROFILES ARE TO BE MADE,
C   SUBROUTINE PPP IS CALLED TO PRESET VALUES.
C
C     THE ORIGINAL SUBROUTINE *RDPROF* (FROM ROKYRD) HAS BEEN MOD-
C   IFIED TO READ THE RIGHT PROFILE FROM THE RIGHT FOLLOWING WHEEL-
C   PATH OF FILE *I*, AND THE LEFT PROFILE FROM THE RIGHT FOLLOWING
C   WHEELPATH OF FILE *I+2* (I+1 IF PAVEMENT IS NOT JRCP), THIS WAS
C   NECESSARY TO ACCOMODATE THE WHEELPATH SEPARATION FOR AIRCRAFT,
C   WHERE TWO PROFILE RUNS ARE MADE, RIGHT AND LEFT OF CENTER.
C
C
      COMMON /GAIN/ GAINR, GAINL
      COMMON /PACK/ ID(5),IN(300)
      COMMON /INICAL/ IFILE, IFP(19), IPDFLG, IPUNCH, IRATIO, N, NBGN,
     1               NEWN, NPNZRO, NREC, NSKB, NSKBN, STD, U
      COMMON /PLOTS/ ISRS(2,3),NFILE,SCL(4),Y1,YD,NPU(3),NPF(3)
      COMMON X(8000),XOUT(8000),Z(8000)
      DIMENSION IO(15000),DATA(15000)
      EQUIVALENCE (IO,DATA,X)
      DATA LREC / 0 /
            N2 = N + N
C
C     BRANCH IF DATA IS TO BE READ FROM TAPE.
          IF (NREC .GE. 0)  GO TO 10
C
C     READ DATA FROM CARDS.
C
      REWIND 2
      CALL RDCARD(N2)
      WRITE (2) (DATA (I),I=1,N2,2)
      WRITE (2) (DATA (I),I=2,N2,2)
      GO TO 35
C
C     POSITION THE TAPE.
   10 CALL POSITP(IFILE,NREC,LREC)
C
C     READ <N> PAIRS OF DECIMATED POINTS FROM TAPE INTO ARRAY <IO>.
      CALL IOTAPE(LREC)
C
C     SCALE THE DATA WHICH HAS JUST BEEN READ.
      DO 30 I=1,N2,2
   30       DATA(I) = IO(I) / GAINR
C
C     STORE DATA ON SCRATCH FILE, RIGHT THEN LEFT.
      REWIND 2
      WRITE (2) (DATA(I),I=1,N2,2)
C
C
C     POSITION TAPE1 TO READ THE LEFT PROFILE FROM THE *LEFT OF CENTER*
C     FILE. FOR JRCP PAVEMENTS, THE LEFT FILE IS THE SECOND FILE AFTER
C     THE RIGHT FILE. THIS SHOULD BE CHANGED TO CORRESPOND WITH THE FILE
C     ARRANGEMENT ON TAPE1 WHEN IT IS DIGITIZED.
C
      IFIL2 = IFILE + 2
      IF (ITYPE .NE. 4HJRCP) IFIL2=IFILE+1
      CALL POSITP(IFIL2,NREC,LREC)
C
      CALL IOTAPE(LREC)
      DO 31 I=1,N2,2
   31 DATA(I+1) = IO(I) / GAINL
      REWIND 2
      READ (2) (DATA(I),I=1,N2,2)
      WRITE (2) (DATA(I),I=2,N2,2)
C
C     PRESET PLOTTING PARAMETERS IF PROFILE PLOTS ARE TO BE MADE.
   35     IF (IFP(3).NE.0 .OR. IFP(9).NE.0)  CALL PPP (N2,IFP)
          IF (IFP(2).NE.0)  CALL PPP(N2,IFP)
C
C     STORE DIFFERENCE PROFILE ON SCRATCH FILE.
      DO 50 I=1,N2,2
   50         DATA(I+1) = DATA(I) - DATA(I+1)
      WRITE (2) (DATA(I),I=2,N2,2)
   60 REWIND 2
          RETURN
      END
```

```
      SUBROUTINE ROCARD (N2)
CC
C     ROCARD - READ IN DATA BY ALTERNATE METHOD (CARDS).
C
C     THIS EXISTING *RDCARD* SUBROUTINE READS CARD IMAGES FROM LOCAL
C     FILES *TAPE1* (RIGHT PROFILE) AND *TAPE* (LEFT PROFILE). THE FIRST
C     TWO CARDS OF EACH DATA FILE CONTAIN A TITLE AND THE NO. OF
C     POINTS IN THE FILE. IN USING CARDS, PROFILE DATA WAS COPIED FROM
C     INPUT (TAPE5) TO *TAPE1* AND *TAPE6*.
C
C
C
      COMMON X(8000),XOUT(8000),Z(8000)
      EQUIVALENCE (X,IO)
      DIMENSION IO(1),TI(8)
      READ (1,1002) TI,NUM
      PRINT 1003,TI,NUM
      READ (6,1002) TI,NUM
      PRINT 1003,TI,NUM
 1002 FORMAT(8A10,/,I5)
      READ (1,1001) (IO(I),I=1,N2,2)
      READ (6,1001) (IO(I),I=2,N2,2)
 1001 FORMAT (8F9.3)
 1003 FORMAT(5X,8A10,/,*    NUMBER OF DATA POINTS =*,I10)
      RETURN
      END
```

```
      SUBROUTINE IOTAPE(LREC)
CC
C     SUBROUTINE IOTAPE READS <N> PAIRS OF DATA PTS FROM TAPE1.  THE
C   DATA IS UNPACKED AND DECIMATED.  THE RESULTS ARE RETURNED IN ARRAY
C   <IO>.
C   ENTRY  : <LREC> = CURRENT RECORD POSITION ON FILE
C   EXIT   : <LREC> = UPDATED TO REFLECT OUTCOME OF TAPE READ
C   <NRPTS> : TOTAL NUMBER OF PTS REMAINING TO BE READ FROM THE TAPE IN
C            ORDER TO OBTAIN <N> DECIMATED PTS FOR EACH WHEELPATH.
C   <NWORDS> : NUMBER OF WORDS TO BE READ FROM THE CURRENT RECORD
C            (300 FOR ALL RECORDS EXCEPT, POSSIBLY, THE LAST).
C   <NXTIO> : POINTER TO THE NEXT AVAILABLE LOCATION IN ARRAY <IO>.
C   <BGNDEC> : POINTER TO FIRST WORD OF <IO> WHICH CONTAINS UNDECIMATED
C            DATA.
C
      COMMON /PACK/ IO(5),IN(300)
      COMMON X(8000),XOUT(8000),Z(8000)
      COMMON /INICAL/ IFILE, IPP(19), IPDFLG, IPUNCH, IRATIO, N, NBGN,
     1            NEWN, NPNZRO, NREC, NSKB, NSKBN, STD, U
      DIMENSION IO(15000)
      EQUIVALENCE (IO,X)
      INTEGER BGNDEC
            IR2 = IRATIO + IRATIO
            NRPTS = N * IR2
            NWORDS = 300
            NXTIO = 1
            BGNDEC = 1
C  RETURN IF NO MORE PTS REMAIN TO BE READ.
   10      IF (NRPTS .LE. 0)  RETURN
      READ(1) IN
           IF (EOF,1)  20,30
C  PROCESSING FOR INSUFFICIENT NUMBER OF RECORDS ON FILE.
   20 PRINT 1000,N,IFILE,NREC
 1000 FORMAT(*0END OF FILE ENCOUNTERED WHILE ATTEMPTING TO READ *I4
     1   * PAIRS OF POINTS*/* FROM FILE NO. *I3* BEGINNING WITH RECORD *
     2   I3)
      CALL ABNORML
   30 LREC = LREC + 1
C  IF AN INCOMPLETE RECORD IS TO BE UNPACKED, SET <NWORDS> TO THE PROPER
C  VALUE.
           IF (NRPTS .LT. 1500)  NWORDS = (NRPTS+4) / 5
            NRPTS = NRPTS - 1500
C  UNPACK DATA INTO ARRAY <IO> BEGINNING WITH <IO(NXTIO)>.  POINTER
C  <NXTIO> IS UPDATED.
      CALL UNPACK (NWORDS,NXTIO,IO)
C  IF DECIMATION IS NOT TO BE PERFORMED, BRANCH TO CONTINUE READING.
           IF (IRATIO .EQ. 1)  GO TO 10
C  PERFORM DATA DECIMATION.  <BGNDEC> IS UPDATED AS EACH TRANSFER IS
C  MADE.
            LAST = NXTIO - 2
      DO 40 I=BGNDEC,LAST,IR2
            IO(BGNDEC) = IO(I)
            IO(BGNDEC+1) = IO(I+1)
            BGNDEC = BGNDEC + 2
   40 CONTINUE
C  UPDATE <NXTIO>.
            NXTIO = BGNDEC
C  CONTINUE READING.
         GO TO 10
      END
```

```
      SUBROUTINE PPP (N2,IFP)
CC
C     PPP - PRESET PARAMETERS FOR PROFILE PLOTS.
C
C     THIS SUBROUTINE DETERMINES PAGE POSITIONING INFORMATION TO BE
C     USED BY THE PROFILE PLOTTING ROUTINES.  IT IS CALLED SOON AFTER
C     THE PROFILE DATA HAS BEEN READ IN. IT ALSO DETERMINES THE
C     DISTANCE FROM THE START OF THE PROFILE MEASUREMENT RUN AS
C     AS FUNCTION OF THE NUMBER OF THE FIRST RECORD BEING READ IN.
C     THIS DISTANCE IS USED AS THE FIRST VALUE ON THE X AXIS OF THE PLOT.
C
      COMMON /PLOTS/ ISRS(2,3),NFILE,SCL(4),Y1,Y0,NPU(3),NPF(3)
      COMMON /DIRECT/ FSTEP, IGAIN, NF, NSEC, NSECN, T, TI(8),
     1                TNP, WAVEL(10) ,YSCAL(10) , XAXL , STRT
      COMMON X(8000),XOUT(8000),Z(8000)
      COMMON /DI/ INK, SKB, DIST, SKA, TOT, USKB, UDIST, USKA, UTOT
      DIMENSION DATA(15000), FAKE(4), IFP(19)
      EQUIVALENCE (DATA,X)
      DATA SCL(1), FAKE(1) / 0,0,0,0 /
C
C     COMPUTE PLOTTER SCALE FACTORS, MAKE SURE THAT THE Y-AXIS CENTERS
C     AROUND ZERO.
      SCL(2) = UDIST
C
C     IF X-AXIS SCALING IS NOT TO BE FORCED, SCALE X-AXIS
C
      IF(XAXL.LE.0.0) GO TO 5
      SCL(4) = UDIST/XAXL
      GO TO 6
    5 CALL SCALE ( SCL, 27.0, 2, 1 )
    6           SCL(3) = SKB
C
C     SCALE Y-AXIS, FIRST DETERMINE MAX. ABSOLUTE VALUE ELEV.
C
                FAKE(2) = ABS( DATA(1) )
      IF(IFP(9).NE.1.OR.IFP(3).NE.1) GO TO 20
      DO 10 I = 1, N2
   10     IF ( ABS( DATA(I) ) .GT. FAKE(2) )  FAKE(2) = ABS( DATA(I) )
      CALL SCALE (FAKE, 2.5, 2, 1)
                YD = FAKE(4)
                Y1 = -2.5 * YD
   20 CONTINUE
C
C     CALCULATE NO. OF POINTS OF UNFILTERED PROFILE PER PAGE.
C
                NPU(1) = 1.0 + ( 9.0 * SCL(4) ) / T
                NPU(2) = MIN0 ( NPU(1), NSEC - NPU(1) + 1 )
                NPU(3) = NSEC - ( NPU(1) + NPU(2) ) + 2
C
C     CALCULATE NO. OF POINTS OF DECIMATED FILTERED PROFILES PER PAGE.
C
                NPF(1) = 1.0 + ( 9.0 * SCL(4) ) / TNP
                NPF(2) = MIN0 ( NPF(1), NSECN - NPF(1) + 1 )
                NPF(3) = NSECN - ( NPF(1) + NPF(2) ) + 2
         RETURN
      END
```

```
      SUBROUTINE DISPLY (J, IPROF, X, XOUT)
CC
C     SUBROUTINE DISPLY PRINTS RESULTS AND CALLS SPECIFIC PLOT ROUTINES
C  AT THE OPTION OF THE USER.
C
      COMMON /CDFPDF/ DX, IPDF, CDF(100), PDF(100), FREQ(10),
     1                PCT(5), NPTS, STEPIN, NP
      COMMON /INICAL/ IFILE, IFP(19), IPDFLG, IPUNCH, IRATIO, N, NBGN,
     1                NEWN, NPNZRO, NREC, NSKB, NSKBN, STD, U
      COMMON /TBL/ STBL(7,3,10)
C
C     STORE VALUES IN SUMMARY TABLE.
C
                STBL(1,IPROF,J) = STD
                STBL(2,IPROF,J) = U
      DO 10 I = 3, 7
   10           STBL(I,IPROF,J) = PCT(I-2)
C
C     IF SPECIFIED, PUNCH DATA TO BE USED IN REGRESSION MODEL.
C
          IF (IPUNCH .EQ. 5HPUNCH)  PUNCH 9000, J, IPROF, STD, U, PCT
 9000 FORMAT (I2,I1,7E11.5)
C
C     IF SPECIFIED, PRINT TABLE OF PDF AND CDF VALUES.
C
      IF (IPDFLG .NE. 0)  CALL PTBL (IPROF, J)
C
C     CALL ANY SPECIFIED PLOTTING ROUTINES.
C  **** PLOTTING ROUTINES  *PLTCDF* , *PLTPDF* HAVE NOT
C         BEEN IMPLEMENTED YET.
C
         IF (IFP(3) .EQ. 1 .AND. IFP(IPROF+3).EQ.1)
     1    CALL PLTPRF (IPROF,0,X(NSKB),0.0,IFP)
         IF (IFP(IPROF+3) .EQ. 0) RETURN
         IF (IFP(9+J) .EQ. 0)  RETURN
C ***    IF (IFP(7) .NE. 0)  CALL PLTCDF
C ***    IF (IFP(8) .NE. 0)  CALL PLTPDF
         IF (IFP(2) .NE. 0) CALL PLTPRF(IPROF,J,X,XOUT,IFP)
         IF (IFP(9) .NE. 0)  CALL PLTPRF (IPROF, J, X, XOUT,IFP)
         RETURN
      END
```

```
      SUBROUTINE PTBL (IPROF, J)
CC
C     PTBL - PRINT TABLE OF PROBABILITY DENSITY (PDF) AND DISTRIBUTION
C            (CDF) FUNCTIONS.
C
      COMMON /PLOTS/ ISRS(2,3),NFILE,SCL(4),Y1,YD,NPU(3),NPF(3)
      COMMON /DIRECT/ FSTEP, IGAIN, NF, NSEC, NSECN, T, TI(8),
     1                TNP, WAVEL(10) ,YSCAL(10) , XAXL , STRT
      COMMON /CDFPDF/ DX, IPDF, CDF(100), PDF(100), FREQ(10),
     1                PCT(5), NPTS, STEPIN, NP
      COMMON /HDG/ HEADER(5), NPAGE
C
C     PRINT HEADING FOR PDF AND CDF TABLE.
C
            NPAGE = NPAGE + 1
      PRINT 1000,HEADER,NPAGE,TI,ISRS(1,IPROF),ISRS(2,IPROF)
 1000 FORMAT(1H1,32X,4A10,A3,I3,///,7X,7A10,A2  /  1H0,33X,2A10
     1    /  1H0,19X*DISCRETE APPROXIMATING PROBABILITY DENSITY (PDF)*
     2    /  17X*AND DISTRIBUTION (CDF) FUNCTIONS FOR MOVING RMS VALUES*
     3    /  1H0,36X*FILTER PASSBAND*  )
      IF (J .EQ. 1)  GO TO 10
      PRINT 1010,FREQ(J),FREQ(J-1),WAVEL(J-1),WAVEL(J)
 1010 FORMAT(25X*FREQUENCY *F6.4* TO *F6.4*  (CYCLES / FT)*
     1    /  29X*WAVELENGTH *F5.1* TO *F5.1*  (FT)*  )
            AVG = NPTS * TNP
      GO TO 20
   10 PRINT 1020,FREQ(1),WAVEL(1)
 1020 FORMAT(24X*FREQUENCY *F6.4* AND HIGHER  (CYCLES / FT)*
     1    /  31X*WAVELENGTH 0 TO *F5.1*  (FT)*  )
            AVG = NPTS * T
   20 PRINT 1030,(PCT(I),I=1,5),U,STD,AVG
 1030 FORMAT(1H0,15X*THE 50, 75, 90, 95, AND 99TH PERCENTILE RMS VALUES*
     1                * ARE :* / 8X,5E14.6
     2    /  1H0,14X*RMS MEAN =*E14.7,7X*STD DEVIATION =*E14.7
     3    /      17X*AVERAGES FOR RMS VALUES COMPUTED OVER*F8.2* FT.*)
      PRINT 1040
 1040 FORMAT(1H0,18X*RMS VALUE (IN.)*8X*PDF*15X*CDF*)
            RMS = DX
C
C     PRINT TABLE OF PDF AND CDF VALUES.
C
      DO 30 I=1,IPDF
      PRINT 1050,RMS,PDF(I),CDF(I)
 1050 FORMAT(21X,F10.5,9X,F8.5,10X,F8.5)
            RMS = RMS + DX
C
C     BRANCH UNLESS BOTTOM OF PAGE REACHED.
         IF (I.NE.38 .AND. I.NE.90)  GO TO 30
            NPAGE = NPAGE + 1
      PRINT 1060, HEADER, NPAGE, TI, ISRS(1,IPROF), ISRS(2,IPROF)
 1060 FORMAT (1H1,32X,4A10,A3,I3,///,8X,7A10,A2,//,33X,2A10
     1    /  1H0,18X*RMS VALUE (IN.)*8X*PDF*15X*CDF*)
   30 CONTINUE
         RETURN
      END
```

```
      SUBROUTINE PLTPRF (IPROF, IBAND, X, XOUT,IFP)
CC
C     PLTPRF - MAKE CALCOMP PLOT OF ROAD PROFILE.
C
C     ENTRY:   (IBAND) = 0 IF ONLY UNFILTERED PROFILE IS TO BE PLOTTED
C                      = J, (1 .LE. J .LE. NF) IF FILTERED OUTPUT OF THE
C                          J TH  PASSBAND IS TO BE PLOTTED IN ADDITION
C                          TO OR INSTEAD OF THE UNFILTERED PROFILE
C              (IPROF) = 1 IF CURRENT PROFILE IS RIGHT PROFILE
C                      = 2 IF LEFT PROFILE
C                      = 3 IF RIGHT - LEFT SERIES (DIFFERENCE PROFILE)
C              (X)     = UNFILTERED PROFILE
C              (XOUT)  = FILTERED PROFILE
C              (NPU)   = NO. OF PTS. OF UNFILTERED PROFILE PER PLOT PAGE
C              (NPF)   = NO. OF PTS. OF DECIMATED PROFILES PER PLOT PAGE
C              (NFILE) = NAME OF PLOT FILE
C              (Y1)    = FIRST VALUE OF Y-AXIS
C              (YD)    = Y-AXIS DISTANCE PER INCH OF PLOT
C              (SCL(3))= FIRST VALUE OF X-AXIS
C              (SCL(4))= X-AXIS DISTANCE PER INCH OF PLOT
C              (IFP(1))= 1 FOR REDUCED PLOT
C              (IFP(2))= 1 FOR FILTERED ONLY PLOT
C     CALLS:   BGNPLT, PLT, AXIS, SYMBOL, LINEP, ENDPLT, MULPLT
C
      COMMON /PLOTS/ ISRS(2,3),NFILE,SCL(4),Y1,YD,NPU(3),NPF(3)
      COMMON /DIRECT/ FSTEP, IGAIN, NF, NSEC, NSECN, T, TI(8),
     1                TNP, WAVEL(10) ,YSCAL(10) , XAXL , STRT
      DIMENSION JPTS(3), HDG(5), X(1), XOUT(1),FAKE(4), IFP(19)
C
C     BRANCH IF ONLY UNFILTERED PROFILE IS TO BE PLOTTED.
         IF (IBAND .EQ. 0)  GO TO 20
C
C     INITIALIZATION OF LOOP IS DEPENDENT ON PASSBAND BEING PLOTTED.
C
         IF (IBAND .EQ. 1)  GO TO 10
      ENCODE ( 50, 1000, HDG )  WAVEL(IBAND-1), WAVEL(IBAND)
 1000 FORMAT(*FILTER PASSBAND :*F6.1,2X*TO*F6.1,2X*FT. WAVELENGTHS*)
            JPTS(1) = NPF(1)
            JPTS(2) = NPF(2)
            JPTS(3) = NPF(3)
            TF = TNP
            JDOT = 1
         GO TO 20
   10 ENCODE ( 50, 1010, HDG )  WAVEL(IBAND)
 1010 FORMAT(*FILTER PASSBAND :   0.0  TO*F6.1,2X*FT. WAVELENGTHS*)
            JPTS(1) = NPU(1)
            JPTS(2) = NPU(2)
            JPTS(3) = NPU(3)
            TF = T
            JDOT = 0
C
C     INITIALIZE PLOT.
C
   20 CALL BGNPLT ( NFILE, 132.0, 20, 10 )
      IF(IFP(1).EQ.1) CALL MULPLT(0,8)
C
C     SET PAGE COUNTER, INITIALIZE FIRST POINT OF X-AXIS.
C
            NPGS = 3
         IF (NPU(3) .LE. 1)  NPGS = 2
```

```
            FIRST = SCL(3)
            IF(STRT.GT.0) FIRST=STRT
            I1STU = 1
            I1STF = 1
      IF(IFP(2).NE.1) GO TO 35
      IF(YSCAL(IBAND).LE.0) GO TO 25
      YD = YSCAL(IBAND)
      Y1 = -2.5*YD
      GO TO 35
C
C     DETERMINE Y-AXIS SCALE FACTORS FOR FILTERED ONLY PLOT
C
   25 FAKE(1)=0.
      FAKE(2)=ABS(XOUT(1))
      DO 30 I=2,NSECN
   30 IF (ABS(XOUT(I)).GT.FAKE(2)) FAKE(2)=ABS(XOUT(I))
      CALL SCALE(FAKE,2,5,2,1)
      YD=FAKE(4)
      Y1=-2.5*YD
      PRINT 31, Y1,YD
   31 FORMAT(*FIRST Y=*,F6.3,*DELTA Y=*,F6.3)
   35 DO 70 IP = 1,NPGS
C
C     DRAW BORDER, SET ORIGIN.
C     IF REDUCED PLOT IS TO BE MADE, BYPASS 8.5X11.0 INCH
C     COORDINATES OF FULL SIZE PLOT.
C
      IF(IFP(1).EQ.1) GO TO 40
      CALL PLT(0,0,0,0,3)
      CALL PLT(0,0,8,5,2)
      CALL PLT(11,0,8,5,2)
      CALL PLT(11,0,0,0,2)
      CALL PLT(0,0,0,0,2)
      CALL PLT(1,0,4,0,-3)
      GO TO 45
   40 CALL PLT ( 0.0, 0.0, 3 )
      CALL PLT ( 0.0, 10.625, 2 )
      CALL PLT ( 13.75, 10.625, 2 )
      CALL PLT ( 13.75, 0.0, 2 )
      CALL PLT ( 0.0, 0.0, 2 )
      CALL PLT ( 2.5, 5.3, -3 )
C
C     DRAW AXES AND ZERO LINE.
C
   45 CALL AXIS (0,0,-2.5,20HPVMT ELEVATION (IN.),20,5,0,90,0,Y1,YD)
      CALL AXIS (0,0,-2.5,29HPOSITION ALONG THE PVMT (FT.),-29,9,0,0,0,
     1           FIRST,SCL(4),0.14,0.105,-1)
      CALL PLT ( 9.0, 0.0, 3 )
      CALL PLT ( 0.0, 0.0, 2 )
C
C     PLOT HEADINGS WHICH DO NOT VARY WITH OPTION BEING PLOTTED.
C
      CALL SYMBOL (-.5,3.1,.14,TI,0,0,72)
      CALL SYMBOL (6.5,2.75,.14,ISRS(1,IPROF),0,0,20)
      ENCODE ( 7, 1020, FRAME )  IP
 1020 FORMAT(*FRAME*I2)
      CALL SYMBOL (7.4,2.5,.14,FRAME,0,0,7)
C
C     PLOT ONE PAGE OF UNFILTERED SERIES, USING SOLID LINE.
C     BRANCH IF ONLY FILTERED SERIES IS TO BE PLOTTED.
C
      IF (IFP(2).NE.0) GO TO 50
C
      CALL LINEP ( T, X(I1STU), NPU(IP), 0 )
C
C     BRANCH IF PLOT IS TO INCLUDE FILTERED PROFILE.
          IF (IBAND .GT. 0)  GO TO 50
C
C     PLOT HEADING FOR PLOT OF ONLY UNFILTERED PROFILE.
C
      CALL SYMBOL (3.26,-3.25,.14,18HUNFILTERED PROFILE,0,0,18)
          GO TO 60
C
C     PLOT HEADING FOR COMBINED FILTERED AND UNFILTERED PROFILES.
C
   50 CALL SYMBOL (1.0,-3.25,.14,HDG,0,0,50)
C
C     IF DOTTED LINE IS TO BE USED, PLOT EXPLANATORY HEADING.
C
          IF (IBAND .EQ. 1)  GO TO 55
          IF (IFP(2).NE.1) GO TO 51
      CALL SYMBOL (1.0,2.75,.14,16HFILTERED PROFILE,0,0,16)
      CALL LINEP (TF,XOUT(I1STF),JPTS(IP),0)
      GO TO 60
   51 CALL SYMBOL (1.0,2.75,.14,23HUNFILTERED - SOLID LINE,0,0,23)
      CALL SYMBOL (1.0,2.5,.14,22HFILTERED - DOTTED LINE,0,0,22)
C
C     PLOT FILTERED PROFILE.
C
   55 CALL LINEP ( TF, XOUT(I1STF), JPTS(IP), JDOT )
   60           FIRST = FIRST + 9.0 * SCL(4)
                I1STU = I1STU + NPU(IP) - 1
                I1STF = I1STF + JPTS(IP) - 1
      CALL PLT ( 0.0, 0.0, 999)
   70 CONTINUE
      CALL ENDPLT
          RETURN
      END
```

AD-A031 754 AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OHIO F/G 14/2
A COMPARISON OF TWO INERTIAL REFERENCE PROFILOMETERS USED TO EV--ETC(U)
MAY 76 C E DOEPKE
UNCLASSIFIED AFIT-CI-76-69 NL

2 OF 2
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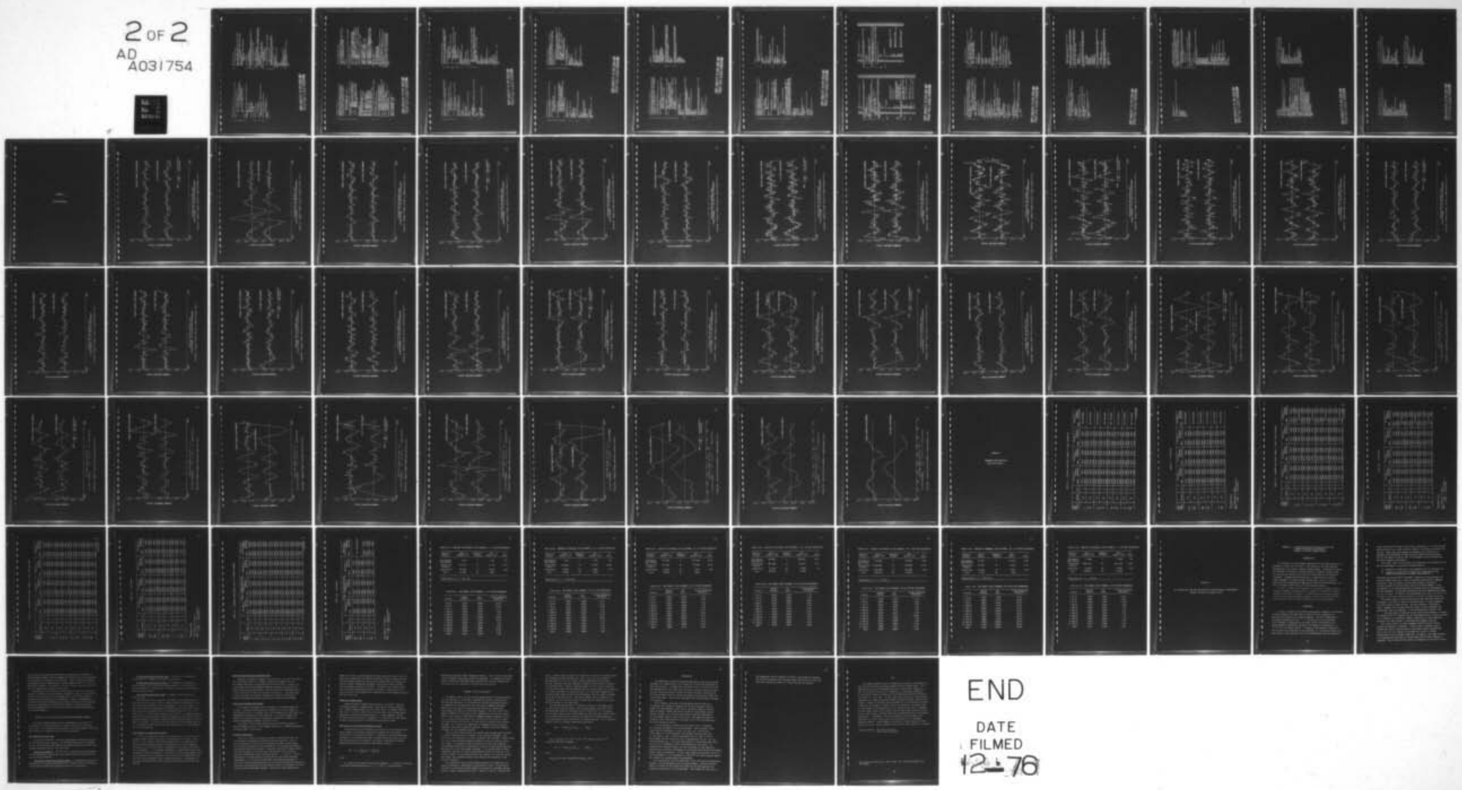

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```
      SUBROUTINE LINEP (T, Y, N, JDOT)
CC
C     LINEP DRAWS A CALCOMP PLOT OF THE PROFILE STORED IN ARRAY <Y>.
C
C     ENTRY:  (T)    = DISTANCE ALONG ROAD BETWEEN PTS.
C             (N)    = NO. OF PTS. TO PLOT
C             (JDOT) : IF .LE. 0, PLOT SOLID LINE (USE ALL PTS.)
C                      IF .GT. 0, PLOT DOTTED LINE (SKIP (JDOT) PTS.
C                                 BETWEEN SUCCESSIVE DOTS)
C             (YD)   = Y-AXIS DISTANCE PER INCH OF PLOT
C             (SCL(4)) = X-AXIS DISTANCE PER INCH OF PLOT
C
C     CALLS:  PLT
C
      COMMON /PLOTS/ ISRS(2,3),NFILE,SCL(4),Y1,YD,NPU(3),NPF(3)
      DIMENSION Y(1)
              DIST = T / SCL(4)
              XCD = 0.0
              YSCL = 1.0 / YD
      CALL PLT ( XCD, Y(1)*YSCL, 3 )
              XSK = JDOT * DIST
              INC = JDOT + 1
      DO 20 I = 2, N, INC
C
C     DRAW LINE TO NEXT POINT.
C
              XCD = XCD + DIST
      CALL PLT ( XCD, Y(I)*YSCL, 2 )
C
C     IF SOLID LINE IS BEING DRAWN, INCREMENT LOOP AND CONTINUE.
          IF(JDOT.LE.0) GO TO 20
C
C     SKIP <JDOT> POINTS BEFORE DRAWING NEXT DOT.
C
              XCD = XCD + XSK
      CALL PLT ( XCD, Y(I+JDOT)*YSCL, 3 )
   20 CONTINUE
          RETURN
      END
```

```
      SUBROUTINE PSS (ITYPE)
CC
C     PSS - PRINT SUMMARY STATISTICS.
C
      COMMON /PLOTS/ ISRS(2,3),NFILE,SCL(4),Y1,YD,NPU(3),NPF(3)
      COMMON /HDG/ HEADER(5), NPAGE
      COMMON /DIRECT/ FSTEP, IGAIN, NF, NSEC, NSECN, T, TI(6),
     1                TNP, WAVEL(10) ,YSCAL(10) , XAXL , STRT
      COMMON /TBL/ STBL(7,3,10)
      DIMENSION PASS(5)
      DATA (PASS(I),I=1,5)/4.0,10.0,25.0,50.0,100.0/
              WAVEL0 = 0.0
              IBAND = 0
C
C     PRINT PAGE HEADING.
C
   10         NPAGE = NPAGE + 1
      PRINT 9000, HEADER, NPAGE, TI
 9000 FORMAT (1H1,57X,4A10,A3,I3,10(/),19X,7A10,A2,//,30X,*SUMMARY *
     + *STATISTICS FOR ROUGHNESS AMPLITUDES (IN.)*/)
C
C     PRINT STATISTICS ONE PASSBAND AT A TIME.
C
   20         IBAND = IBAND + 1
      PRINT 9010, WAVEL0, WAVEL(IBAND)
 9010 FORMAT (1H0,40X,F5.1,* TO *F5.1* FT. WAVELENGTHS*,/,32X*STANDARD*
     + 31X,*PERCENTILE*,/,32X,*DEVIATION*,4X,*MEAN*,7X,*50*,8X,*75*,8X,
     + *90*,8X,*95*,8X,*99*)
      DO 30 IPROF = 1, 3
   30 PRINT 9020, ISRS(1,IPROF), ISRS(2,IPROF),
     +           ( STBL(I,IPROF,IBAND), I = 1, 7 )
 9020 FORMAT (11X,2A10,7F10.5)
          IF (IBAND .GE. NF) GO TO 40
              WAVEL0 = WAVEL(IBAND)
C
C     SKIP TO NEXT PAGE IF 5TH PASSBAND WAS JUST SUMMARIZED.
C
          IF (IBAND - 5)  20, 10, 20
C
C     CALL SUBROUTINE SI TO COMPUTE SI VALUES IF THERE ARE
C     5 WAVELENGTHS SPECIFIED AND IF THE WAVELENGTHS ARE :
C     4.0 , 10.0 , 25.0 , 50.0 , 100.0 .
C
   40 IF(NF.LT.5) RETURN
      DO 50 I=1,NF
   50 IF(WAVEL(I).EQ.PASS(1)) GO TO 55
      RETURN
   55 I=I+1
      J=I+3
      KK=1
      DO 60 K=I,J
      KK=KK+1
   60 IF(WAVEL(K).NE.PASS(KK)) RETURN
      NPAGE = NPAGE + 1
      PRINT 9030, HEADER, NPAGE, TI
 9030 FORMAT(1H1,57X,4A10,A3,I3,10(/),19X,7A10,A2)
      CALL SI (ITYPE,I,NF)
      RETURN
      END
```

```
      SUBROUTINE SI (ITYPE,K,NF)
CC
C     THIS SUBROUTINE COMPUTES AND PRINTS SI VALUES FOR OVERALL
C     ROUGHNESS AND FOR INDIVIDUAL PASSBANDS. THE ROUGHNESS
C     MEASURES ARE STORED IN ARRAY STBL (SEE SUBROUTINE PSS,
C     WHICH CALLS THIS ROUTINE). THIS SUBROUTINE COMPUTES
C     SI VALUES FOR OVERALL ROUGHNESS AND FOR THE PASSBANDS :
C      4 - 10 FT.,10 - 25 FT., 25 - 50 FT.,50 - 100 FT.
C
C      ITYPE:   DEFINES THE PAVEMENT TYPE.
C               (SEE THE COMMENTS IN THE MAIN PROGRAM IN
C                THE INPUT PARAMETER LIST)
C
C     THE INDICES OF THE TRIPLY DIMENSIONED ARRAY STBL(I,J,K) HAVE
C     THE FOLLOWING MEANINGS :
C      I = 1,2,...,7  CORRESPONDS TO THE SEVEN ROUGHNESS MEASURES :
C                      SIGMA,MEAN,50,75,90,95,99 PERCENTILES.
C      J = 1,2,3      CORRESPONDS TO THE RIGHT,LEFT,OR DIFFERENCE
C                     PROFILES.
C      K = 2,3,4,5    CORRESPONDS TO THE PASSBANDS LISTED ABOVE.
C      K = 1          CORRESPONDS TO THE PASSBAND 0.0 TO 4.0 FT.
C                     WHICH IS NOT USED.
C
      COMMON /TBL/STBL(7,3,10)
      DIMENSION IPAVE(2)
      REAL M250,M290,M350,M390,M450,M490,M550,M590
      REAL LONG10,LONG25,LONG50,LONG100
      DATA IPAVE(1),IPAVE(2)/8H  RIGID ,8HFLEXIBLE/
      TYPE = 0.0
      M250 = 0.5 * (STBL(3,1,K) + STBL(3,2,K))
      M290 = 0.5 * (STBL(5,1,K) + STBL(5,2,K))
      M350 = 0.5 * (STBL(3,1,K+1) + STBL(3,2,K+1))
      M390 = 0.5 * (STBL(5,1,K+1) + STBL(5,2,K+1))
      M450 = 0.5 * (STBL(3,1,K+2) + STBL(3,2,K+2))
      M550 = 0.5 * (STBL(3,1,K+3) + STBL(3,2,K+3))
      M590 = 0.5 * (STBL(5,1,K+3) + STBL(5,2,K+3))
      IF(ITYPE.EQ.4HCRCP.OR.ITYPE.EQ.4HJRCP) GO TO 1000
C
C     MODEL TO COMPUTE SI VALUES IF ROAD SECTION IS FLEXIBLE PAVEMENT.
C
      IF(ITYPE.EQ.4HST  ) TYPE = 1.0
      M490 = 0.5 * (STBL(5,1,K+2) + STBL(5,2,K+2))
C
C     SI VALUES USING BOTH TRANSVERSE AND LONGITUDINAL WAVES.
      OVERALL = 110.325*M250 - 23.2817*M290 - 23.4597*M390 -
     A          100.543*STBL(3,3,K) + 21.2896*STBL(5,3,K) +
     B          12.0121*STBL(3,3,K+1) - 3.25599*STBL(3,3,K+3) + 4.8504
       PASS10 = 144.063*M250 - 74.0006*M290 - 112.808*STBL(3,3,K) +
     C          25.5075*STBL(5,3,K) + 0.195997*TYPE + 4.7104
       PASS25 = 33.9286*M350 - 37.7821*M390 - 43.8993*STBL(3,3,K+1) +
     D          16.4489*STBL(5,3,K+1) + 4.6977
       PASS50 = 85.1875*(M450**2) - 14.3068*M490 -
     E          24.0718*STBL(3,3,K+2) + 11.3604*STBL(5,3,K+2) -
     F          0.39628*TYPE + 4.5729
       PASS100 = (-9.66499)*STBL(3,3,K+3) + 4.1992
C
C     SI VALUES USING LONGITUDINAL WAVES ONLY.
      LONG10 = (-31.2349)*M290 + 4.3776
      LONG25 = (-42.5285)*M350 + 4.4884
      LONG50 = (-8.8719)*M490 + 4.1254
      LONG100 = (-7.5642)*M550 + 4.0950
C
C     SI VALUES USING TRANSVERSE WAVES ONLY.
      TRAN10 = 13.5346*STBL(5,3,K) - 99.0353*STBL(3,3,K) + 5.1274
      TRAN25 = 11.7797*STBL(5,3,K+1) - 57.5225*STBL(3,3,K+1) + 4.4690
      TRAN50 = (-13.5636)*STBL(3,3,K+2) + 3.9792
      TRAN100 = (-9.6650)*STBL(3,3,K+3) + 4.1992
      KK=2
      GO TO 600
C
C     MODEL TO COMPUTE SI VALUES IF ROAD SECTION IS RIGID PAVEMENT.
C
 1000 IF(ITYPE.EQ.4HCRCP) TYPE = 1.0
C
C     SI VALUES USING BOTH TRANSVERSE AND LONGITUDINAL WAVES.
      OVERALL = (-41.86155)*M250 - 23.1302*M350 - 2.51141*M550 +
     A          15.72015*STBL(5,3,K) + 0.4596960*TYPE + 4.90744
       PASS10 = (-76.22339)*M250 - 13.0937*M290 + 22.43115*STBL(5,3,K) +
     B          0.5952396*TYPE + 4.57096
       PASS25 = 6.549039*STBL(5,3,K+1) - 35.2290*M350 + 0.901372*TYPE +
     C          4.51926
       PASS50 = 2.86560*STBL(5,3,K+2) - 14.86519*M450 + 0.6961390*TYPE +
     D          4.05997
       PASS100 = (-4.917895)*M550 + 0.82757*TYPE + 3.92022
C
C     SI VALUES USING LONGITUDINAL WAVES ONLY.
      LONG10 = (-39.2150)*M250 + 4.5532
      LONG25 = 13.6313*M390 - 51.1418*M350 + 4.0983
      LONG50 = (-14.0837)*M450 + 4.6494
      LONG100 = 7.9216*M590 - 22.0906*M550 + 4.6297
C
C     SI VALUES USING TRANSVERSE WAVES ONLY.
      TRAN10 = 31.5260*STBL(5,3,K) - 122.4020*STBL(3,3,K) + 5.2126
      TRAN25 = 16.5952*STBL(5,3,K+1) - 47.4536*STBL(3,3,K+1) + 4.4733
      TRAN50 = 17.3990*STBL(5,3,K+2) - 46.5144*STBL(3,3,K+2) + 4.4205
      TRAN100 = (-7.2676)*STBL(3,3,K+3) + 4.2600
      KK=1
  600 PRINT 100, IPAVE(KK), ITYPE
      PRINT 101, OVERALL
      PRINT 102
      PRINT 103, PASS10,TRAN10,LONG10
      PRINT 104, PASS25,TRAN25,LONG25
      PRINT 105, PASS50,TRAN50,LONG50
      PRINT 106, PASS100,TRAN100,LONG100
  100 FORMAT(//,54X,*S I   V A L U E S*//35X,*THIS PVMT SECTION IS *
     1A8,* PAVEMENT OF TYPE *A4,/)
  101 FORMAT(45X,*ALL PASSBANDS CONSIDERED:*,F10.4)
  102 FORMAT(//,26X,*PASSBAND*,14X,*COMBINED*,13X,*TRANSVERSE*,11X,
     1*LONGITUDINAL*)
  103 FORMAT(/,21X,* 4.0 TO  10.0 FT.*,8X,F10.4,2(12X,F10.4))
  104 FORMAT(/,21X,*10.0 TO  25.0 FT.*,8X,F10.4,2(12X,F10.4))
  105 FORMAT(/,21X,*25.0 TO  50.0 FT.*,8X,F10.4,2(12X,F10.4))
  106 FORMAT(/,21X,*50.0 TO 100.0 FT.*,8X,F10.4,2(12X,F10.4))
      RETURN
      END
```

```
      SUBROUTINE PCTILE(C,M,DX,X)
CC
C     THIS SUBROUTINE INTERPOLATES IN A TABLE OF VALUES OF A PROBABILITY
C     DISTRIBUTION FUNCTION TO FIND THE FOLLOWING UPPER PERCENTILE
C     POINTS OF THE DISTRIBUTION - 50, 75, 90, 95, 99.
C
C     THE INPUTS ARE AS FOLLOWS.
C     C       ARRAY OF VALUES OF THE DISTRIBUTION FUNCTION.
C     M          NO. OF POINTS IN C.
C     DX         STEP SIZE OF THE RANDOM VARIABLE. CALL THE R.V. R.
C                THEN C(I)=P(R LE I*DX).
C
C     THE OUTPUTS ARE AS FOLLOWS.
C     X          X(I), I=1 TO 5 ARE THE 50, 75, 90, 95, AND 99TH
C                UPPER PERCENTILE POINTS.
C
      DIMENSION C(1),X(1),P(5)
      DATA (P(I),I=1,5)/.5,.75,.9,.95,.99/
      IF(M.LE.1 .OR. DX.LE.0.) GO TO 10
      K=1
      DO 1 I=1,5
      DO 2 J=K,M
      IF(P(I).GT.C(J)) GO TO 2
      JJ=J
      IF(J.GT.1) GO TO 3
      X(I)=P(I)*DX/C(1)
      GO TO 1
    3 X(I)=(J-1.+(P(I)-C(J-1))/(C(J)-C(J-1)))*DX
      GO TO 1
    2 CONTINUE
C
C        ERROR MESSAGE
      PRINT 12,P(I),M,C(M)
   12 FORMAT(*0ERROR IN PCTILE - PROBABILITY*,E20.8,* GT C(M)=*,I5,*)=*,
     1       E20.8)
      STOP
    1 K=JJ
      RETURN
C
C        ERROR MESSAGE
   10 PRINT 11,M,DX
   11 FORMAT(*0ERROR IN INPUT TO PCTILE, M,DX=*,I5,E20.8)
      STOP
      END
```

```
      SUBROUTINE DISPDF(X,N,M,Z,C,DX,U,STD)
CC
C     THIS SUBROUTINE COMPUTES THE DISCRETE APPROXIMATING PROBABILITY
C     DENSITY FUNCTION OF AN INPUT SAMPLE OF NON-NEGATIVE VALUES.
C     ALSO, THE MEAN AND STANDARD DEVIATION ARE COMPUTED.
C
C     THE INPUTS ARE AS FOLLOWS.
C     X          ARRAY OF INPUT VALUES.
C     N          SAMPLE SIZE.  N GE 2.
C     M          NO. OF CELLS FOR P.D.F., EQUAL IN LENGTH.
C
C     THE OUTPUTS ARE AS FOLLOWS.
C     Z          ARRAY OF PROBABILITIES.  Z(I)=P((I-1)*DX LE X LE I*DX)
C                M*DX=MAX OF THE X(I).
C     C       SAMPLE DISTRIBUTION FUNCTION.  C(I)=P(X LE I*DX).
C     DX         DEFINED ABOVE.
C     U          MEAN.
C     STD        STANDARD DEVIATION.
C
      DIMENSION X(1),Z(1),C(1)
      IF(N.LT.2) GO TO 5
C **** FIND THE STEP SIZE OF THE P.D.F.
      RN=1./N
      DX=X(1)
      DO 1 I=2,N
    1 IF(X(I).GT.DX) DX=X(I)
      DX=DX/M
C **** INITIALIZE THE Z-ARRAY.
      DO 2 I=1,M
    2 Z(I)=0.
C
C        COMPUTE COUNTS IN EACH CELL, THEN CONVERT THESE TO PROBABILI-
C        TIES.
C        NOTE THAT RDX MUST BE SLIGHTLY SMALLER THAN 1./DX SO THAT
C        THE MAXIMUM X(I) WILL AUTOMATICALLY BE COUNTED IN THE MTH AND
C        NOT THE (M+1)ST CELL.
C        ALSO COMPUTE THE MEAN AND STANDARD DEVIATION.
      RDX=.999999/DX
      STD=0.
      U=0.
      DO 3 I=1,N
      STD=STD+X(I)*X(I)
      U=U+X(I)
      K=X(I)*RDX
      K=K+1
      Z(K)=Z(K)+1.
    3 CONTINUE
      STD=SQRT((STD-RN*U*U)/(N-1))
      U=U*RN
      Z(1)=Z(1)*RN
      C(1)=Z(1)
      DO 4 I=2,M
      Z(I)=Z(I)*RN
    4 C(I)=C(I-1)+Z(I)
      RETURN
C **** ERROR MESSAGE.
    5 PRINT 6,N
    6 FORMAT(*0ERROR IN DISPDF    N=*,I5)
      STOP
      END
```

```
      SUBROUTINE MOVESQ(X,N,M,Z,NZ)
CC
C     THIS SUBROUTINE COMPUTES THE LOCAL RMS VALUE CENTERED AT EACH
C     POINT OF AN INPUT TIME SERIES.
C
C     THE INPUTS ARE AS FOLLOWS.
C     X         ARRAY OF TIME SERIES VALUES.
C     N         NO. OF POINTS IN ARRAY X.
C     M         NO. OF POINTS TO USE IN EACH RMS CALCULATION.
C               0 LT M LE N.
C
C     THE OUTPUTS ARE AS FOLLOWS.
C     Z         ARRAY OF RMS VALUES.  THE FIRST Z-VALUE CORRESPONDS
C               TO THE (M/2+1)ST X-POINT, AND THE LAST Z-VALUE
C               CORRESPONDS TO THE (N-(M-M/2-1))ST X-POINT.
C               (M/2 IS TRUNCATED AS IN INTEGER ARITHMETIC.)
C               IN OTHER WORDS, VALUES THAT WOULD HAVE HAD END EFFECTS
C               ARE NOT COMPUTED.
C     NZ        NO. OF Z POINTS COMPUTED.
C
      DIMENSION X(1),Z(1)
      IF(M.LE.0 .AND. M.GT.N) GO TO 3
      RM=1./M
C
C        COMPUTE THE FIRST POINT.
      SUM=0.
      DO 1 I=1,M
    1 SUM=SUM+X(I)*X(I)
      Z(1)=SQRT(SUM*RM)
      NZ=N-M+1
      IF(M.EQ.N) RETURN
C
C        NOW COMPUTE THE REMAINING VALUES RECURSIVELY.
      I1=0
      I2=M
      DO 2 I=2,NZ
      I1=I1+1
      I2=I2+1
      SUM=SUM-X(I1)*X(I1)+X(I2)*X(I2)
      IF (SUM .LT. 0.0)  SUM = 0.0
      Z(I)=SQRT(SUM*RM)
    2 CONTINUE
      RETURN
C
C       ERROR MESSAGE
    3 PRINT 4,M,N
    4 FORMAT(*0ERROR IN MOVESQ   M,N,*,2I5)
      STOP
      END
```

```
      SUBROUTINE GAIN2(G2,N,WC,DW,T)
CC
C     THIS SUBROUTINE COMPUTES SQUARED GAIN VS. FREQUENCY OF A
C     FILTER DESIGNED BY SUBROUTINE COEFLW.
C     NOTE THAT IF THE FILTER IS APPLIED TWICE, AS IN SUBROUTINE
C     FILTER, THE GAIN OF THE DOUBLE FILTER IS THE SQUARED GAIN OF
C     THE ORIGINAL FILTER.
C
C     THE INPUTS ARE AS FOLLOWS.
C     N         IF N GT 0, N= NO. OF EQUALLY SPACED POINTS AT WHICH THE
C               SQUARED GAIN IS TO BE COMPUTED.  THE FREQUENCY
C               POINTS ARE J*DW, J=0,1, . . . (N-1).
C               IF N LT 0, THEN THE FREQUENCY POINTS ARE ASSUMED TO BE
C               DW(J), J=1,2, . . . -N.
C     WC     CUTOFF FREQUENCY - COMPUTED IN SUBROUTINE COEFLW.
C     DW        SEE ABOVE.
C               ALL FREQUENCIES MUST BE IN RADIANS.
C     T         STEP SIZE OF THE INDEPENDENT VARIABLE.
C
C     THE OUTPUTS ARE AS FOLLOWS.
C     G2        ARRAY OF SQUARED GAINS.
C
      DIMENSION G2(1),DW(1)
      T2=T*.5
      B=1./TAN(WC*T2)
      IF(N.LT.0) GO TO 50
      DWT=DW(1)*T2
      WT=0.
      DO 1 I=1,N
      G2(I)=1./(1.+(TAN(WT)*B)**12)
    1 WT=WT+DWT
      RETURN
   50 NN=-N
      DO 2 I=1,NN
    2 G2(I)=1./(1.+(TAN(DW(I)*T2)*B)**12)
      RETURN
      END
```

```
      SUBROUTINE COEFLW(W1,AA,T,A,B,IFLAG,WC)
CC
C     THIS SUBROUTINE COMPUTES THE COEFFICIENTS FOR THE LOW-PASS FILTER
C     WITH APPROXIMATING SQUARED-MAGNITUDE FUNCTION GIVEN BY EQ. (49A),
C     P. 150, OF RADER AND GOLD/S PAPER (R AND G) IN PROC. IEEE, FEB.,
C     1967, WITH N=6.  THE WEIGHTS ARE COMPUTED SO THAT THE SQUARED GAIN
C     AT FREQUENCY W1 IS AA, 0 LT AA LT 1.
C
C     THE RECURSIVE FILTER IS OF THE FORM
C     Y(K)=A(1)*X(K) + SUM J=1 TO 6 OF (A(J+1)*X(K-J)-B(J)*Y(K-J)).
C
C     THE INPUTS ARE AS FOLLOWS.
C     W1,AA     PARAMETERS WHICH DEFINE THE FILTER (SEE COMMENTS ABOVE).
C               W1 MUST BE IN RADIANS PER UNIT CHANGE IN THE
C               INDEPENDENT VARIABLE.
C     T         STEP SIZE OF THE INDEPENDENT VARIABLE.
C
C     THE OUTPUTS ARE AS FOLLOWS.
C     A,B       ARRAYS OF COEFFICIENTS FOR THE FILTER.  (SEE COMMENTS
C               ABOVE.)
C     IFLAG     =0 IF THE CUTOFF FREQUENCY OF THE APPROXIMATING
C               SQUARED-MAGNITUDE FUNCTION IS GREATER THAN
C               THE NYQUIST FREQUENCY, 1./(2T).  IN THIS CASE,
C               THE COEFFICIENTS ARE NOT COMPUTED.
C               =1 IF A LE 0 OR A GE 1.  IN THIS CASE, THE COEFFICIENTS
C               ARE NOT COMPUTED.
C               =2 OTHERWISE.
C     WC     CUTOFF FREQUENCY IN RADIANS OF THE FILTER.  (THE SQUARED
C               GAIN IS .5 AT WC.)
C
      DIMENSION P(3),Q(3),A(1),B(1)
      DATA F3/.261799388/
      IF(0..LT.AA .AND. AA.LT.1.) GO TO 20
      IFLAG=1
      RETURN
   20 ANG=W1*T*.5
C
C     COMPUTE THE TANGENT OF (WC*T)/2, WHERE WC IS THE CUTOFF FREQUENCY
C     OF THE SQUARED-MAGNITUDE APPROXIMATING FUNCTION.
      TWC=TAN(ANG)*(AA/(1.-AA))**.0833333333333
      WC=ATAN(TWC)
      IF(WC.LT.0.) WC=WC+6.283185308
      WC=WC*2./T
      IF(WC.GT.0. .AND. WC.LT.3.141592654/T) GO TO 10
      IFLAG=0
      RETURN
   10 IFLAG=2
      F1=2.*TWC
      F2=TWC*TWC
C
C     COMPUTE THE RETAINED POLES IN THE FIRST TWO QUADRANTS - THE OTHER
C     RETAINED POLES ARE COMPLEX CONJUGATES OF THESE.
      AM=7.
      DO 1 I=1,3
      RDEN=1./(1.-F1*COS(F3*AM)+F2)
      U=(1.-F2)*RDEN
      V=F1*SIN(F3*AM)*RDEN
      AM=AM+2.
C        U + I*V AND U - I*V ARE POLES.
      P(I)=-2.*U
      Q(I)=U*U+V*V
    1 CONTINUE
C
C     USE THE POLES TO COMPUTE THE COEFFICIENTS OF Z IN THE DENOMINATOR
C     OF THE SYSTEM FUNCTION, H(Z) (R AND G, P. 152, EQ. (11)).
      GG0=Q(1)*Q(2)
      GG1=P(1)*Q(2)+P(2)*Q(1)
      GG2=Q(2)+P(1)*P(2)+Q(1)
      GG3=P(1)+P(2)
      B(1)=P(3)+GG3
      B(2)=GG2+P(3)*GG3+Q(3)
      B(3)=GG1+P(3)*GG2+Q(3)*GG3
      B(4)=GG0+P(3)*GG1+Q(3)*GG2
      B(5)=P(3)*GG0+Q(3)*GG1
      B(6)=Q(3)*GG0
C
C     WE MUST COMPUTE THE GAIN AT FREQUENCY ZERO SO THAT WE CAN SCALE
C     H(Z) TO MAKE THE GAIN EQUAL TO ONE AT ZERO FREQUENCY AND NEAR ONE
C     WITHIN THE PASSBAND.  BY SCALING H(Z), WE MULTIPLY THE GAIN AT ALL
C     FREQUENCIES BY THE SAME CONSTANT.
      F=1.
      DO 2 I=1,6
    2 F=F+B(I)
      F=F/64.
C
C     NOW F IS THE RECIPROCAL OF THE GAIN AT ZERO.  SINCE THE UNSCALED
C     NUMERATOR OF H(Z) IS (Z+1)**6, THE SCALED COEFFICIENTS ARE BI-
C     NOMIAL COEFFICIENTS MULTIPLIED BY F.
      A(1)=F
      A(2)=6.*F
      A(3)=15.*F
      A(4)=20.*F
      A(5)=A(3)
      A(6)=A(2)
      A(7)=F
      RETURN
      END
```

```fortran
      SUBROUTINE FILTER(X,N,QQ,Q,H,Z,Y)
CC
C     THIS SUBROUTINE PERFORMS LOW-PASS FILTERING USING THE COEFFICIENTS
C     COMPUTED IN SUBROUTINE COEFLW.
C     FILTERING IS PERFORMED FORWARD AND THEN THE OUTPUT IS FILTERED
C     BACKWARD TO ACHIEVE ZERO PHASE SHIFT AT ALL FREQUENCIES.
C     THE RECURSIVE FILTER IS OF THE FORM
C     Y(K)=QQ*X(K) + SUM J=1 TO 6 OF (Q(J)*X(K-J)-H(J)*Y(K-J)).
C
C     THE INPUTS ARE AS FOLLOWS.
C     X          ARRAY TO BE FILTERED.
C     N          NO. OF PTS. IN ARRAY X.
C                N GE 7.
C     QQ,Q(I),   COEFFICIENTS FOR THE FILTER - SEE COMMENTS ABOVE.
C     H(I)
C
C     THE OUTPUTS ARE AS FOLLOWS.
C     Z          FILTERED ARRAY.  Z MUST BE DIMENSIONED AT LEAST N.
C
C     Y          WORKING ARRAY WHICH MUST BE DIMENSIONED AT LEAST N.
C                THE NECESSITY OF THE LARGE WORKING ARRAY Y COULD BE
C                ELIMINATED AT THE EXPENSE OF INCREASED EXECUTION TIME.
C
      DIMENSION X(1),Y(1),Z(1),Q(1),H(1)
      IF(N.LT.7) GO TO 19
C
C        FIRST FILTER FORWARD.
C
C        COMPUTE THE POINTS THAT HAVE LEFT-END EFFFCTS.
      Y(1)=QQ*X(1)
C
C     EXTEND THE FIRST ORDINATE TO THE LEFT, I.E., ASSUME X(I)=X(1),
C     IF I .LT. 6, TO AVOID A DISCONTINUITY AT TIME ZERO.  THE
C     LAST ORDINATE SHOULD BE EXTENDED TO THE RIGHT IN THE INPUT ARRAY
C     TO AVOID A DISCONTINUITY AND TO ALLOW THE TRANSIENTS TO DIE OUT
C     IN THE FORWARD FILTER BEFORE THE BACKWARD FILTER IS BEGUN.  DIS-
C     CONTINUITIES CAUSE HIGH-FREQUENCY FILTER-INDUCED TRANSIENT EFFECTS
C
      SUM=0.
      DO 20 LL=1,6
   20 SUM=SUM+Q(LL)
      SUM=SUM*X(1)
      Y(1)=Y(1)+SUM
      DO 1 J=2,6
      Y(J)=X(J)*QQ
      L=J-1
      DO 21 LL=1,L
      NN=J-LL
   21 Y(J)=Y(J)+Q(LL)*X(NN)-H(LL)*Y(NN)
      SUM=SUM-(Q(L)*X(1))
      Y(J)=Y(J)+SUM
    1 CONTINUE
C
C        COMPUTE TERMS THAT HAVE NO END EFFECTS.
      DO 2 J=7,N
      SUM=X(J)*QQ
      DO 3 LL=1,6
      NN=J-LL
    3 SUM=SUM+Q(LL)*X(NN)-H(LL)*Y(NN)
      Y(J)=SUM
    2 CONTINUE
C
C         NOW, FILTER THE FORWARD-FILTERED TIME SERIES BACKWARDS TO
C         OBTAIN A FILTERED TIME SERIES WITH ZERO PHASE SHIFT AT ALL
C         FREQUENCIES.
C
C         COMPUTE THE TERMS THAT HAVE RIGHT-END EFFECTS.
      Z(N)=QQ*Y(N)
      NTEST=N-5
      J=N
   15 J=J-1
      Z(J)=Y(J)*QQ
      L=N-J
      DO 16 LL=1,L
      NN=J+LL
   16 Z(J)=Z(J)+Q(LL)*Y(NN)-H(LL)*Z(NN)
      IF(J.GT.NTEST) GO TO 15
C
C         COMPUTE THE TERMS THAT HAVE NO END EFFECTS.
   17 J=J-1
      SUM=Y(J)*QQ
      DO 18 LL=1,6
      NN=J+LL
   18 SUM=SUM+Q(LL)*Y(NN)-H(LL)*Z(NN)
      Z(J)=SUM
      IF(J.GT.1) GO TO 17
      RETURN
C
C          ERROR MESSAGE
   19 PRINT 11,N
   11 FORMAT(*0N=*,I20,10X,*TERMINATE EXECUTION IN SUBROUTINE FILTER*)
      STOP
      END
```

```
          IDENT    UNPACK                                                UNPACK
          TITLE    UNPACK: UNPACKS DATA FROM ROAD PROFILE TAPE.          UNPACK
          SPACE    2                                                     UNPACK
          ENTRY    UNPACK                                                UNPACK
         SPACE     2                                                     UNPACK
***   UNPACK IS A FORTRAN-CALLABLE SUBROUTINE WHICH UNPACKS DATA FROM    UNPACK
*  ARRAY <IN> OF COMMON BLOCK /PACK/ INTO AN ARRAY SPECIFIED BY THE      UNPACK
*  CALLING PROGRAM.                                                      UNPACK
*     CALLING SEQUENCE:                                                  UNPACK
*          CALL UNPACK(NWORDS,NXTIO,IO)                                  UNPACK
*     WHERE:                                                             UNPACK
*  <NWORDS> : NUMBER OF WORDS TO BE UNPACKED.                            UNPACK
*  <IO> : ARRAY TO RECIEVE UNPACKED DATA.                                UNPACK
*  <NXTIO> : POINTER TO NEXT AVAILABLE LOCATION IN ARRAY <IO>.           UNPACK
*             (THIS POINTER IS UPDATED AND RETURNED TO THE CALLING PRO-  UNPACK
*              GRAM.)                                                    UNPACK
*     IN ADDITION, THE CALLING PROGRAM MUST DECLARE:                     UNPACK
*          COMMON /PACK/ ID(5),IN(300)                                   UNPACK
*     WRITTEN BY JOHN C. OQUIN, FEB. 3, 1974.                            UNPACK
         SPACE     2                                                     UNPACK
**    THE WORDS OF ARRAY <IN> MUST EACH CONTAIN FIVE 12-BIT INTEGERS.    UNPACK
*  NEGATIVE VALUES ARE ASSUMED TO BE IN 2 S COMPLEMENT NOTATION AND ARE UNPACK
*  CONVERTED TO 1 S COMPLEMENT.                                          UNPACK
          SPACE    4                                                     UNPACK
          USE      /PACK/                                                UNPACK
          BSS      5                                                     UNPACK
IN        BSS      300                                                   UNPACK
          USE      *                                                     UNPACK
          EJECT                                                          UNPACK
          VFD      42/0LUNPACK,18/3                                      UNPACK
UNPACK    EQX                                                            UNPACK
          SB7      1                                                     UNPACK
          SB6      -B7                                                   UNPACK
          MX0      12                 MASK FOR PICKING UP BYTE 4         UNPACK
          SX5      4                                                     UNPACK
          SA2      B1                 LIMIT FOR OUTER LOOP               UNPACK
          SB1      X2                                                    UNPACK
          SA4      B2                 VALUE OF <NXTIO>                   UNPACK
          SX4      X4+B6                                                 UNPACK
          SB4      B0                 INITIALIZE COUNTER FOR OUTER LOOP  UNPACK
LOOP1     SA1      IN+B4              PUT WORD TO BE UNPACKED INTO X1    UNPACK
          SB5      X5                 INITIALIZE BYTE COUNTER TO 4       UNPACK
LOOP2     BX6      X0*X1              PUT BYTE 4 OF X1 INTO X6           UNPACK
          AX6      48                 SHIFT, EXTENDING SIGN BIT          UNPACK
*   THE NUMBER IS ASSUMED TO BE IN 2 S COMPLEMENT, HENCE THERE IS NO     UNPACK
*   NEGATIVE ZERO TO CONTEND WITH.                                       UNPACK
          PL       X6,STORE           BRANCH IF NUMBER IS NON-NEGATIVE   UNPACK
          SX6      X6+B6              CONVERT NEGATIVE VALUE TO 1 S COMPL. UNPACK
STORE     SA6      B3+X4              STORE UNPACKED NUMBER              UNPACK
          SX4      X4+B7                                                 UNPACK
          ZR       B5,INCR            BRANCH IF WORD COMPLETELY UNPACKED UNPACK
          SB5      B5+B6                                                 UNPACK
          LX1      12                                                    UNPACK
          EQ       LOOP2              PROCESS NEXT BYTE OF X1            UNPACK
INCR      SB4      B4+B7                                                 UNPACK
          LT       B4,B1,LOOP1        BRANCH IF WORDS REMAIN TO BE UNPACKEDUNPACK
          SX7      X4+B7                                                 UNPACK
          SA7      B2                 UPDATE POSITION POINTER (<NXTIO>)  UNPACK
          EQ       UNPACKX                                               UNPACK
          END                                                            UNPACK
```

```
          IDENT    GETID                                                 GETID
          TITLE    GETID: UNPACKS IDENT RECORD                           GETID
          SPACE    2                                                     GETID
          ENTRY    GETID                                                 GETID
          SPACE    2                                                     GETID
***   GETID IS A FORTRAN-CALLABLE SUBROUTINE WHICH UNPACKS THE IDENT     GETID
*  RECORD OF ONE OF THE CFHR ROAD PROFILE TAPES.                         GETID
*                                                                        GETID
*     CALLING SEQUENCE:                                                  GETID
*          CALL GETID                                                    GETID
*                                                                        GETID
*     IN ADDITION THE CALLING PROGRAM MUST DECLARE:                      GETID
*          COMMON /PACK/ ID(5),IN(300)                                   GETID
*     WHERE:                                                             GETID
*  <IN> : CONTAINS THE PACKED TWO-WORD IDENT RECORD IN LOCATIONS 1 AND 2GETID
*  <ID> : RETURNS THE UNPACKED INFORMATION.                              GETID
*        (<ID(3)> IS NOT PRESENTLY BEING USED, SO IT IS NOT UNPACKED.)  GETID
*                                                                        GETID
*     ALL IDENT INFORMATION IS ASSUMED TO CONTAIN NON-NEGATIVE NUMBERS.  GETID
*                                                                        GETID
*     WRITTEN BY JOHN C. OQUIN, FEB. 3, 1974.                            GETID
          SPACE    4                                                     GETID
          USE      /PACK/                                                GETID
ID        BSS      5                                                     GETID
IN        BSS      300                                                   GETID
          USE      *                                                     GETID
          EJECT                                                          GETID
          VFD      42/0LGETID,18/0                                       GETID
GETID     EQX                                                            GETID
          MX0      24                                                    GETID
          LX0      24                                                    GETID
          SB1      1                                                     GETID
          SB2      ID                                                    GETID
          SA1      IN                 LOAD X1 AND X2 WITH PACKED IDENT   GETID
          SA2      A1+B1              WORDS FROM TAPE.                   GETID
          LX1      24                                                    GETID
          BX7      X0*X2                                                 GETID
          BX6      X0*X1                                                 GETID
          SA7      B2+4               STORE LAST FIELD IN <ID(5)>        GETID
          SA6      B2                 STORE FILE NO. (1ST FIELD) IN <ID(1)>GETID
          LX1      24                                                    GETID
          LX2      60-24                                                 GETID
          BX6      X0*X1                                                 GETID
          BX7      X0*X2                                                 GETID
          SA6      B2+B1              STORE NO. OF RECORDS IN <ID(2)>    GETID
          SA7      A7-B1              STORE SECTION NO. IN <ID(4)>       GETID
          EQ       GETIDX                                                GETID
          END                                                            GETID
```

```
      SUBROUTINE POSITP(IFILE,NREC,LREC)
CC
C     SUBROUTINE POSITP POSITIONS FILE TAPE1 TO RECORD <NREC> OF FILE
C  <IFILE>.  FILES MAY BE SKIPPED FORWARD, BUT NOT BACKWARD.  WHEN A
C  FILE IS REFERENCED FOR THE FIRST TIME THE IDENT RECORD IS READ AND
C  RELEVANT INFORMATION IS PRINTED.  RECORDS MAY BE SKIPPED BOTH BACK-
C  WARDS AND FORWARDS.
C     <LREC> : POINTER TO THE RECORD AT WHICH THE TAPE IS CURRENTLY
C              POSITIONED.  (THIS VARIABLE IS UPDATED TO REFLECT REPOSI-
C              TIONING DONE BY THE SUBROUTINE.)
C     <LFILE> : POINTER TO CURRENT FILE AT WHICH THE TAPE IS POSITIONED.
C     <IFILE> : FILE TO WHICH THE TAPE IS TO BE REPOSITIONED.
C     CALLS:  SKIPF,SKIPR,BKSP
C
      COMMON /PACK/ ID(5),IN(300)
      DATA LFILE / 1 /
      DATA ITAPE1 / 5LTAPE1 /
      NSK=IFILE-LFILE
C  DETERMINE FILE POSITIONING NEEDED.
      IF(NSK) 90,20,30
C  TAPE POSITIONED TO CORRECT FILE.  BRANCH IF IDENT RECORD NEEDS TO BE
C  READ.
   20 IF(LREC.EQ.0) GO TO 40
      GO TO 50
C  SKIP FORWARD TO PROPER FILE.
   30 CALL SKIPF(ITAPE1,NSK)
      LFILE=IFILE
C  READ IDENT RECORD FORM THE TAPE.
   40 READ(1) IN(1),IN(2)
      CALL GETID
      PRINT 1010,ID(1),ID(4),ID(2)
 1010 FORMAT(* FILE: *I3,5X*SECTION: *I5,5X*NO. OF RECORDS: *I3)
      LREC=1
C  CHECK FOR INCORRECT VALUE IN <NREC>.
C     <NREC> : RECORD TO WHICH TAPE IS TO BE POSITIONED.
   50 IF (NREC.GT.ID(2)) GO TO 95
C  DETERMINE RECORD POSITIONING NEEDED.
      NSK=NREC-LREC
      LREC=NREC
      IF (NSK) 80,70,60
C  SKIP FORWARD <NSK> RECORDS.
   60 CALL SKIPR(ITAPE1,NSK)
   70 RETURN
C
C  BACKSPACE <NSK> RECORDS.
   80 NSK=-NSK
      CALL BKSP(ITAPE1,NSK)
      RETURN
C
C       ERROR MESSAGES
   90 PRINT 1000,IFILE,LFILE
 1000 FORMAT(*0-----ERROR, FILE *I3* IS OUT OF SEQUENCE*/* PREVIOUS FILE
     1 REFERENCED WAS NUMBER *I3,1H.)
      CALL ABNORML
   95 PRINT 1020,NREC,IFILE,ID(2)
 1020 FORMAT(*0IT IS IMPOSSIBLE TO POSITION THE TAPE TO RECORD *I3
     1       * OF FILE *I3,1H,/* THAT FILE HAS ONLY *I3* RECORDS IN *
     2       *ALL.*)
      CALL ABNORML
      END
```

```
      SUBROUTINE SKIPF(FNAME,NSK)
CC
C     SUBROUTINE SKIPF MAKES A PP CALL TO POSITION A LOCAL FILE.
C  <FNAME> : THE FILE TO BE POSITIONED.
C            (MUST BE LEFT JUSTIFIED, ZERO FILL)
C  <NSK> : NUMBER OF LOGICAL UNITS TO SKIP.
C  THERE ARE THREE ENTRY POINTS, DETERMINING THE OPERATION PERFORMED:
C     SKIPF : SKIPS <NSK> FILE(S) FORWARD.
C     SKIPR : SKIPS <NSK> RECORD(S) FORWARD.
C     BKSP :  SKIPS <NSK> RECORD(S) BACKWARD.
C
C     CALLS: GETFET
C
      DIMENSION MEM(1)
      INTEGER FET,RA,FNAME
      DATA LASTF / 0 /
C
C  SET CIO OPERATION CODE, DEPENDING ON THE ENTRY POINT CALLED.
      ICODE=300
      GO TO 10
C
      ENTRY SKIPR
      ICODE=2400
      GO TO 10
C
      ENTRY BKSP
      ICODE=6400
C
C  BRANCH IF <FNAME> IS THE SAME AS THE LAST FILE REFERENCED.
   10 IF (FNAME .EQ. LASTF) GO TO 15
      CALL GETFET (FNAME,FET,RA,MEM)
C
C  <FET> : ADDRESS OF FILE ENVIRONMENT TABLE FOR FILE <FNAME>.
C          (OBTAINED BY GETFET)
      LASTF = FNAME
C
C  BRANCH IF FET HAS NOT BEEN USED YET.
      IF( (MEM(RA+FET).A.7777770) .EQ. 0 ) GO TO 20
C
C  WAIT FOR FET NOT BUSY.
   15 IF((MEM(RA+FET).A.1) .NE. 1 ) CALL PP(4LRCLP,FET)
C
C  SET OPERATION CODE IN THE FET.
   20 MEM(RA+FET)=(MEM(RA+FET).A.7L;;;;;;;;) .O. ICODE
C
C  CALL CIO TO POSITION FILE.
      CALL PP(4LCIOP,NSK,FET)
      RETURN
      END
```

```
      SUBROUTINE GETFET (FNAME,FET,RA,MEM)
CC
C     SUBROUTINE GETFET SETS <FET> TO THE ADDRESS OF THE FILE ENVIRON-
C  MENT TABLE FOR FILE <FNAME>.
C     <MEM> : ARRAY USED FOR DIRECTLY REFERENCING MEMORY.
C     <RA> : NEGATIVE NUMBER SUCH THAT <MEM(RA)> IS THE REFERENCE ADD-
C           RESS OF THE PROGRAMS FIELD LENGTH.
C
      DIMENSION MEM(1)
      INTEGER RA,FET,FNAME
      RA=1-LOCF(MEM)
C
C  SEARCH TABLE OF FILES FOR ENTRY <FNAME>.
      DO 10 I=1,40
   10 IF( (MEM(RA+1+I).A.7L;;;;;;;) .EQ. FNAME ) GO TO 20
C
C  IF THE DO LOOP IS EXHAUSTED, THE FILE CANNOT BE FOUND.
      PRINT 1000,FNAME
 1000 FORMAT(* FILE *A7* NOT FOUND IN TABLE*)
      CALL ABNORML
C
C  MASK OUT THE FET ADDRESS AND STORE IT IN <FET>.
   20 FET=MEM(RA+1+I).A.777777B
      RETURN
      END
```

```
      SUBROUTINE PREFILT(X,N,IFILT,NPNZRO,XOUT,FPRAM,NPRAM)
      DIMENSION X(8000),XOUT(8000),Y(1)
C
C  SUBROUTINE *PREFILT* IS A COMBINATION OF THREE SUBROUTINES USED
C  IN ASSOCIATION WITH THE DIGITAL FILTERING SUBROUTINE PROVIDED
C  BY THE AIR FORCE WEAPONS LABORATORY.
C
C  THE OPERATIONS THROUGH STATEMENT NO. 5 WERE FORMALLY SUBROUTINE
C  *LINOT* WHICH REMOVE A LINEAR TREND FROM THE PROFILE ARRAY, AD-
C  JUSTING THE 1ST AND NTH POINTS TO ZERO.
C
      ASAVE=X(1)
      ASAVE2=X(N)-ASAVE
      DO 5 I=1,N
    5 Y(I)=X(I)-ASAVE-ASAVE2*(I-1)/FLOAT(N-1)
C
C  THE FOLLOWING OPERATIONS, FORMALLY SUBROUTINE *ZAUG*, EXTEND
C  BOTH ENDS OF THE PROFILE ARRAY, ADDING *NZERO* ZEROS TO EACH
C  END OF THE ARRAY.
C
      NZERO = NPNZRO - N
      DO 10 I=1,NZERO
   10 XOUT(I)=0.0
      DO 20 I=1,N
      IA=NPNZRP+I
   20 XOUT(IA)=Y(I)
      DO 30 I=1,NZERO
      IB=NZERO + N + I
   30 XOUT(IB)=0.0
      NPPL=N+NZERO+NZERO
C
C  THE CALLS TO *RVRSE* AND *FILTER2*, FORMALLY SUBROUTINE *BAKFIL*,
C  FILTER THE ARRAY BACKWARDS AND THEN FORWARDS.
C
      DO 40 I=1,2
      CALL RVRSE(XOUT,NPPL)
   40 CALL FILTER2(IFILT,XOUT,NPPL,FPRAM,NPRAM)
C
C  THE FOLLOWING OPERATIONS, FORMALLY SUBROUTINE *SEC*, REMOVE THE
C  EXTENDED ZEROS, RETURNING THE FILTERED PROFILE ARRAY SIZE TO THAT
C  OF THE ORIGINAL UNFILTERED ARRAY.
C
      DO 50 I=1,N
   50 XOUT(I)=XOUT(I+NZERO)
      RETURN
      END
```

```
      SUBROUTINE RVRSE(A,NPTS)
      DIMENSION A(1)
C
C     THIS SUBROUTINE REVERSES THE ORDER OF THE FIRST *NPTS* ELEMENTS
C     OF THE ARRAY *A*.
C
      II=(NPTS+1)/2
      DO 1 I=1,II
      NN=NPTS-I+1
      ASAVE=A(I)
      A(I)=A(NN)
      A(NN)=ASAVE
    1 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE FILTER2(IF,F,NX,FPRAM,NPRAM)
CC  THIS SUBROUTINE PERFORMS DIGITAL FILTERING IN ONE DIRECTION ONLY
C   USING THE COEFFICIENTS DETERMINED IN SUBROUTINES *BPDES*,*BSDES*,
C   *LPDES*, AND *HPDES*. BANDPASS, BANDSTOP, LOWPASS, AND HIGHPASS
C   FILTERING ARE POSSIBLE WITH THIS SUBROUTINE.
C   THIS SUBROUTINE WAS PROVIDED BY THE U.S. AIR FORCE WEAPONS
C   LABORATORY, KIRTLAND AIR FORCE BASE, ALBUQUERQUE, NEW MEXICO.
C
C   THE INPUTS ARE AS FOLLOW:
C    IF    DETERMINES IF COEFFICIENTS OF THE FILTER MUST BE CALCULATED.
C          IF G.T.1 INDICATES NO NEW CALCULATION OF COEFFICIENTS. IF
C          IS USUALLY ALWAYS EQUAL TO 1.
C
C    F     THE PROFILE ARRAY.
C
C   NX     THE NUMBER OF POINTS IN THE PROFILE ARRAY *F*.
C
C   FPRAM PARAMETERS DEFINING THE FILTER (SEE COMMENTS ON *WAVEL(I)*
C   NPRAM IN THE INPUT GUIDE AT THE BEGINNING OF THIS PROGRAM.
C
C   THE OUTPUT IS:
C
C    F    THE FILTERED ARRAY.
C
      DIMENSION F(1),X(11,5),A(20),B(20),C(20),D(20),E(20),AP(20,4)
      DIMENSION NPRAM(4),FPRAM(6)
      TYPE REAL NF
      FC =FPRAM(1)
      FC1=FPRAM(2)
      FC2=FPRAM(3)
      FP =FPRAM(4)
      FP1=FPRAM(5)
      FP2=FPRAM(6)
      NLP=NPRAM(1)
      NHP=NPRAM(2)
      NSB=NPRAM(3)
      NPB=NPRAM(4)
      IF(IF.GT.1)GO TO 9
      PRINT 90
      NP=0
      IF(NLP.EQ.0)GO TO 20
      PRINT 91,FC,NLP
      CALL LPDES(FC,T,NLP,A,B,C,D,E,AP,NP)
      NP=NP+NLP/2
   20 IF(NHP.EQ.0)GO TO 30
      PRINT 92,FP,NHP
      CALL HPDES(FP,T,NHP,A,B,C,D,E,AP,NP)
      NP=NP+NHP/2
   30 IF(NSB.EQ.0)GO TO 40
      CALL    BSDES(FC1,FP2,T,NSB,A,B,C,D,E,AP,NP)
      PRINT 93,FC1,FP2,NSB
      NP=NP+NSB/2
   40 IF(NPB.EQ.0)GO TO 50
      CALL    BPDES(FP1,FC2,T,NPB,A,B,C,D,E,AP,NP)
      NP=NP+NPB/2
      PRINT 94, FP1,FC2,NPB
   50 NP1=NP+1
      NF=1/(2*T)
      PRINT 95,T,NF
    9 DO  1  N=1,11
```

```
      DO  1 M=1,5
  1   X(N,M)=0.
 10 CONTINUE
      DO  5  M=1,NX
      X(1,5)=F(M)
      DO   2  N=1,NP
      TEMP=A(N)*(X(N,5)+AP(N,1)*X(N,4)+AP(N,2)*X(N,3)+AP(N,3)*X(N,2)+
     1AP(N,4)*X(N,1))-B(N)*X(N+1,4)
  2 X(N+1,5)=TEMP-C(N)*X(N+1,3)-D(N)*X(N+1,2)-E(N)*X(N+1,1)
      DO   4  N=1,NP1
      DO   4  MM=1,4
  4 X(N,MM)=X(N,MM+1)
  5 F(M)=X(NP1,5)
 90 FORMAT(///25X,*YOU HAVE REQUESTED*)
 91 FORMAT(3X,*A LOW PASS FILTER WITH CUT OFF FREQUENCY OF*,E13.5,*HER
     1TZ AND OF ORDER*,I3)
 92 FORMAT(3X,*A HIGH PASS FILTER WITH THE PASS BAND BEGINING AT*,E13.
     15,*HERTZ AND OF ORDER*,I3)
 93 FORMAT(3X,*A BAND STOP FILTER BEGINING AT*,E13.5,*HERTZ AND ENDING
     1 AT*,E13.5,*HERTZ AND OF ORDER*,I3)
 94 FORMAT(3X,*A BAND PASS FILTER BEGINING AT*,E13.5,*HERTZ AND ENDING
     1 AT*,E13.5,*HERTZ AND OF ORDER*,I3)
 95 FORMAT(/20X,*THE DATA RATE IS*,E20.8,*AND THE NYQUIST FREQUENCY IS
     1*,F15.5)
 96 FORMAT(     ///3X,*THE DIGITAL FILTER HAS*,I2,*SECTIONS IN CASCADE.
     1 THE KTH SECTION HAS THE TRANSFER FUNCTION*,/14X,
     255HA(K)*(Z**4+AP(K,1)*Z**3+AP(K,2)*Z**2+AP(K,3)*Z+AP(K,4)),/1X,*H(
     3Z)=-----------------------------------------------------------------
     4------*,/18X,36HZ**4+B(K)*Z**3+C(K)*Z**2+D(K)*Z+E(K))
 97 FORMAT(//20X,*CASCADE EQUATION NO.*,I2,/4X,
     15HA(K)=,E22.13,10X,5HB(K)=,E22.13,/2X,
     28HAP(K,1)=,E22.13,10X,5HC(K)=,E22.13,/2X,
     28HAP(K,2)=,E22.13,10X,5HD(K)=,E22.13,/2X,
     28HAP(K,3)=,E22.13,10X,5HE(K)=,E22.13,/2X,
     28HAP(K,4)=,E22.13)
 99 FORMAT(4I2,2X,7E10.0)
      RETURN
      END
```

```
      SUBROUTINE  BPDES(F1,F2,T,N,A,B,C,D,E, AP,NP)
CC
C  THIS SUBROUTINE DESIGNS A BANDPASS DIGITAL FILTER
C
      DIMENSION A(20),B(20),C(20),D(20),E(20),AP(20,4)
      PI=3.1415926536
      W1=SIN(F1*PI*T)/COS(F1*PI*T)
      W2=SIN(F2*PI*T)/COS(F2*PI*T)
      WC=W2-W1
      Q=WC*WC+2.*W1*W2
      S=W1*W1*W2*W2
      KMAX=N/2
      DO 150  K=1,KMAX
      CS=COS(FLOAT(2*K+N-1)*PI/FLOAT(2*N))
      P=-2.*WC*CS
      R=P*W1*W2
      X=1.+P+Q+R+S
       L=K+NP
      A(L)=WC*WC/X
      AP(L,1)=AP(L,3)=0.0
      AP(L,2)=-2.0
      AP(L,4)=1.0
      B(L)=(-4.-2.*P+2.*R+4.*S)/X
      C(L)=(6.-2.*Q+6.*S)/X
       D(L)=(-4.+2.*P-2.*R+4.*S)/X
150    E(L)=(1.-P+Q-R+S)/X
      RETURN
      END
```

```
      SUBROUTINE  BSDES(F1,F2,T,N,A,B,C,D,E, AP,NP)
CC
C     THIS SUBROUTINE DESIGNS A BANDSTOP DIGITAL FILTER.
C
      DIMENSION A(20),B(20),C(20),D(20),E(20),AP(20,4)
      PI=3.1415926536
      W1=SIN(F1*PI*T)/COS(F1*PI*T)
      W2=SIN(F2*PI*T)/COS(F2*PI*T)
      WC=W2-W1
      Q=WC*WC+2.*W1*W2
      S=W1*W1*W2*W2
      Q1=1.0-W1*W2
      P1=1.0+W1*W2
      P2=P1*P1 $Q2=Q1*Q1
      KMAX=N/2
      DO 150  K=1,KMAX
       L=K+NP
      CS=COS(FLOAT(2*K+N-1)*PI/FLOAT(2*N))
      P=-2.*WC*CS
      R=P*W1*W2
      X=1.+P+Q+R+S
      A(L)=P2/X
      AP(L,1)=AP(L,3)=-4*Q1/P1
      AP(L,2)=2.0+4.0*(Q2/P2)
      AP(L,4)=1.0
      B(L)=(-4.-2.*P+2.*R+4.*S)/X
      C(L)=(6.-2.*Q+6.*S)/X
       D(L)=(-4.+2.*P-2.*R+4.*S)/X
150    E(L)=(1.-P+Q-R+S)/X
      RETURN
      END
```

```
      SUBROUTINE LPDES(FC,T,N,A,B,C,D,E,AP,NP)
CC
C     THIS SUBROUTINE DESIGNS A LOWPASS DIGITAL FILTER.
C
      DIMENSION A(20),B(20),C(20),D(20),E(20),AP(20,4)
      PI=3.1415926536
      WCP=SIN(FC*PI*T)/COS(FC*PI*T)
      NMAX=N/2
      NACT=2*NMAX
      DO 120 K=1,NMAX
      CS=COS((2*K+NACT-1)*PI/(2*NACT))
      X=1.0/(1+WCP*WCP-2*WCP*CS)
      L=K+NP
      D(L)=E(L)=0.0
      A(L)=WCP *WCP*X
      AP(L,1)=2.0
      AP(L,2)=1.0
      AP(L,3)=AP(L,4)=0.0
      B(L)=2*(WCP*WCP-1.0)*X
120   C(L)=(1+WCP*WCP+2*WCP*CS)*X
      RETURN
      END
```

```
      SUBROUTINE HPDES(FC,T,N,A,B,C,D,E,AP,NP)
CC
C     THIS SUBROUTINE DESIGNS A HIGHPASS DIGITAL FILTER.
C
      DIMENSION A(20),B(20),C(20),D(20),E(20),AP(20,4)
      PI=3.1415926536
      WCP=SIN(FC*PI*T)/COS(FC*PI*T)
      NMAX=N/2
      NACT=2*NMAX
      DO 120 K=1,NMAX
      CS=COS((2*K+NACT-1)*PI/(2*NACT))
      X=1.0/(1+WCP*WCP-2*WCP*CS)
      L=K+NP
      D(L)=E(L)=0.0
      A(L)=X
      AP(L,1)=-2.0
      AP(L,2)=1.0
      AP(L,3)=AP(L,4)=0.0
      B(L)=2*(WCP*WCP-1.0)*X
120   C(L)=(1+WCP*WCP+2*WCP*CS)*X
      RETURN
      END
```

APPENDIX 2

PLOTTED PROFILES

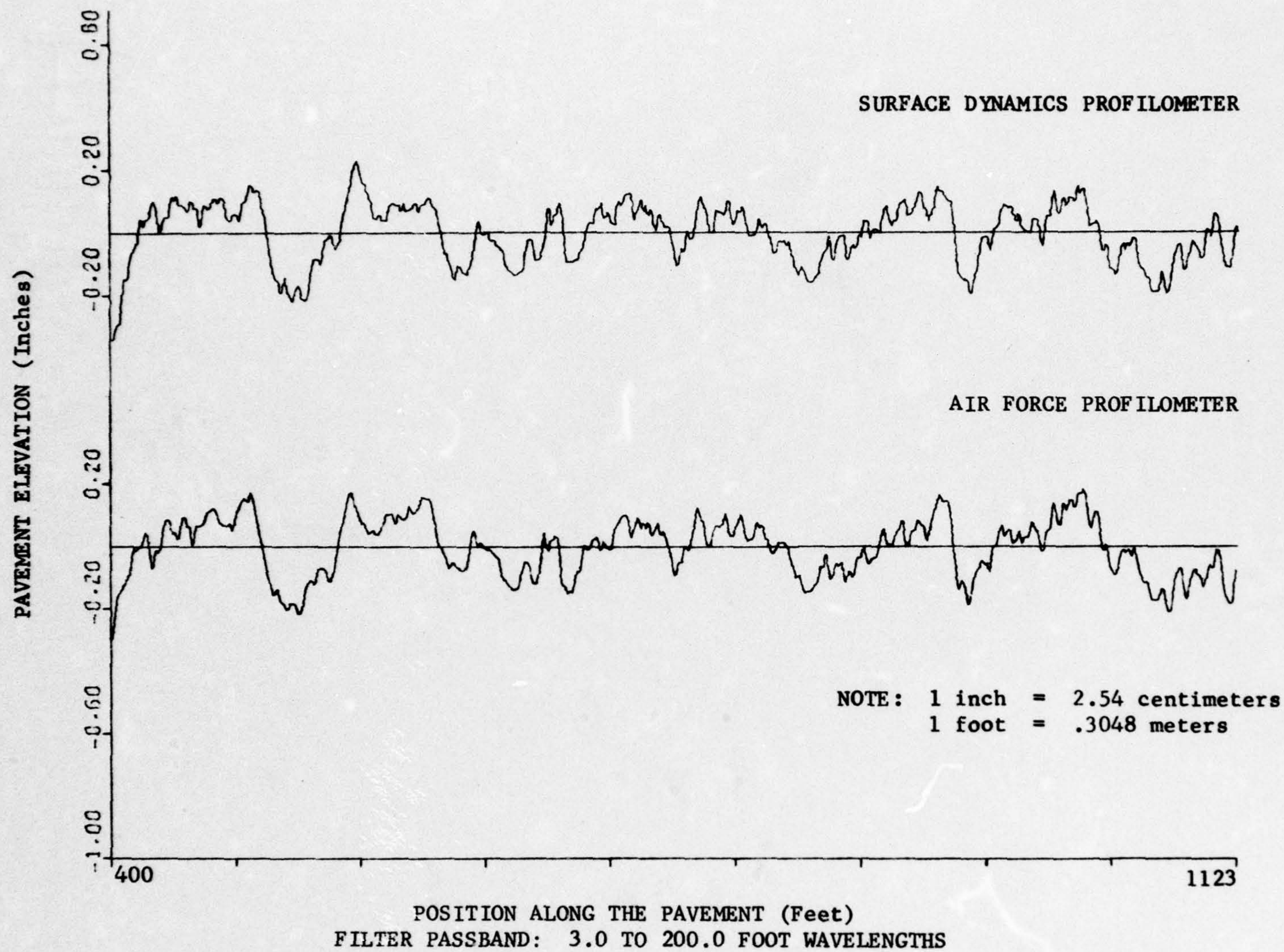


Fig A2.1a. Runway 17 Right, Section A, Right-of-Center, File 1.

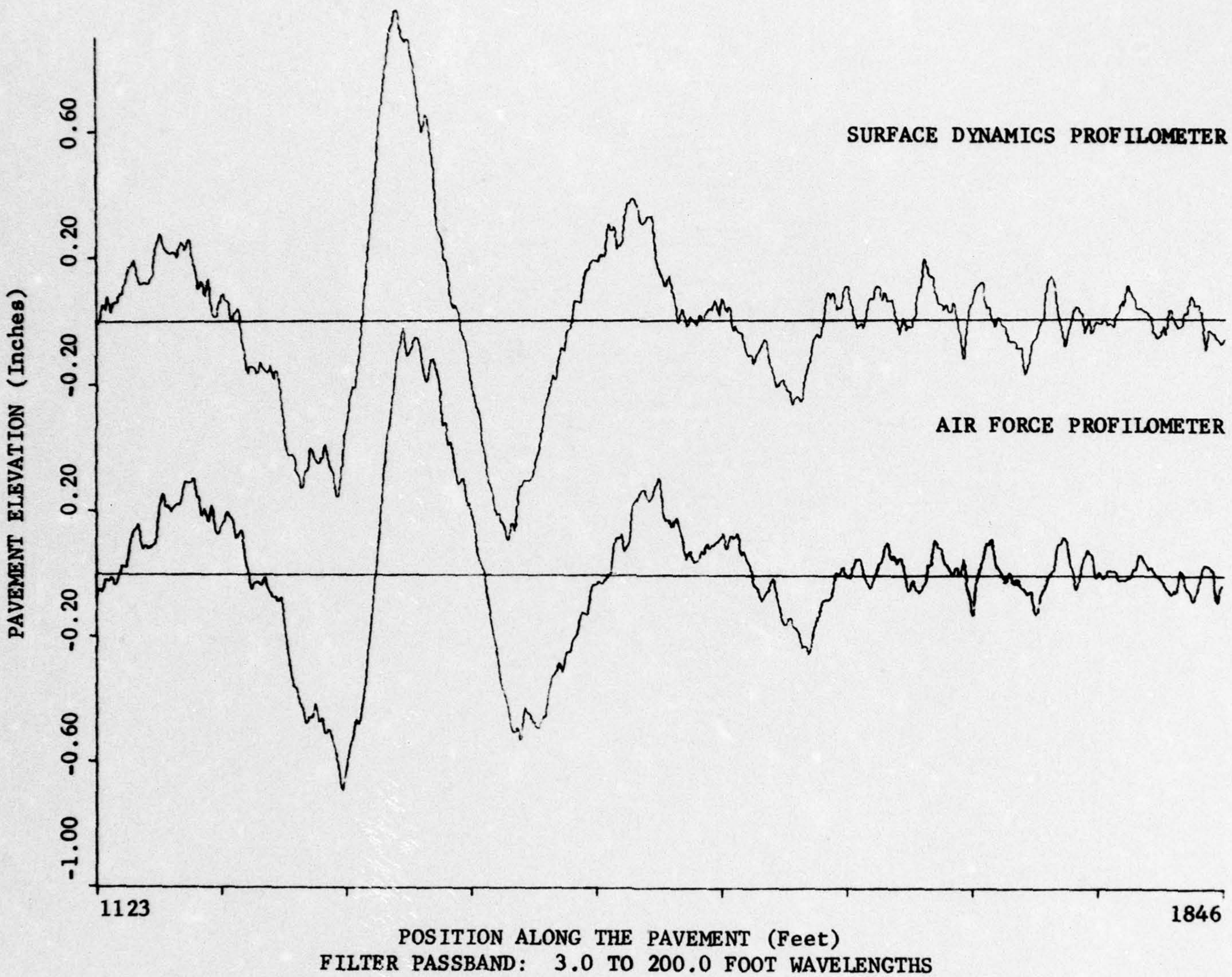


Fig A2.1b. Runway 17 Right, Section A, Right-of-Center, File 1.

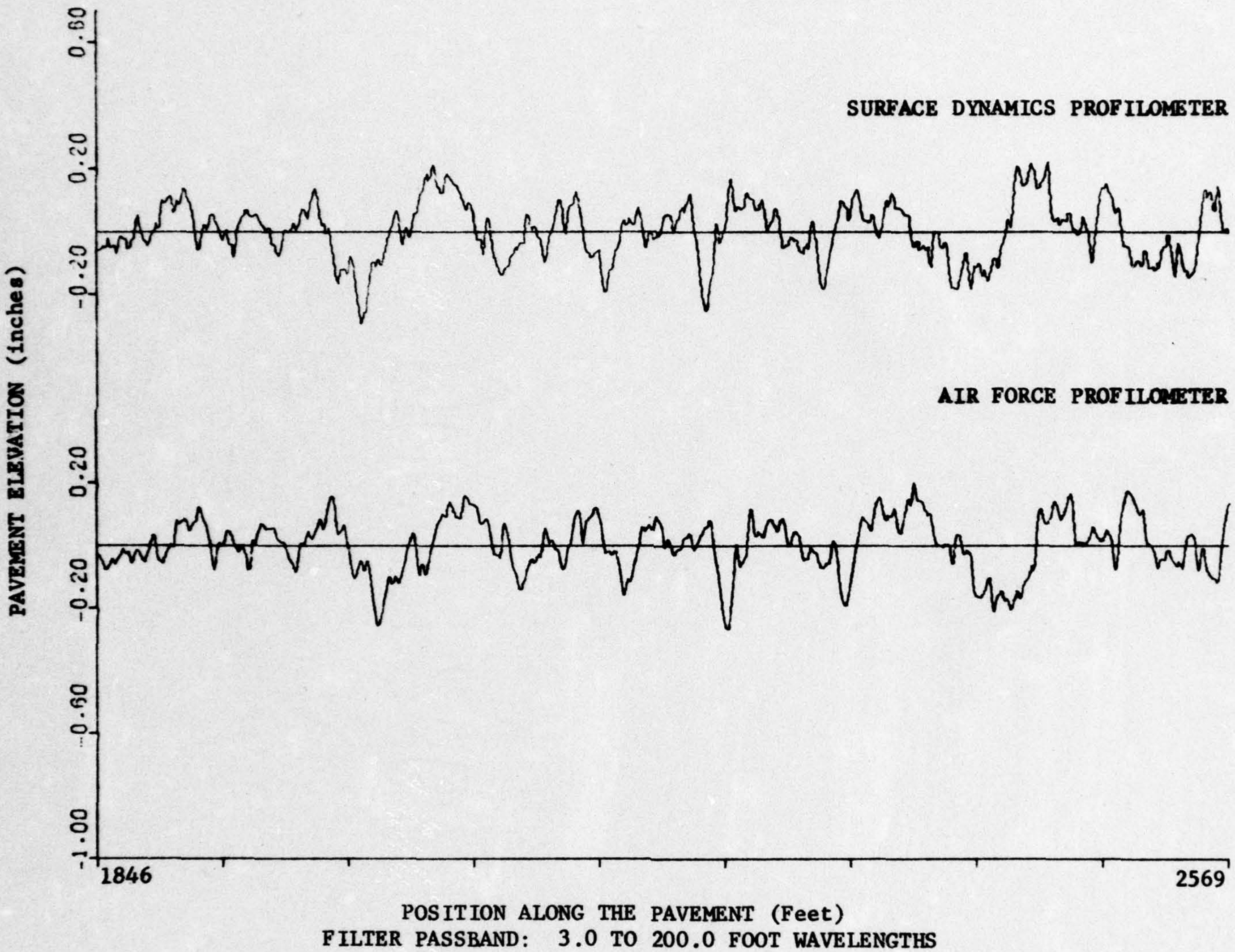


Fig A2.1c. Runway 17 Right, Section A, Right-of-Center, File 1.

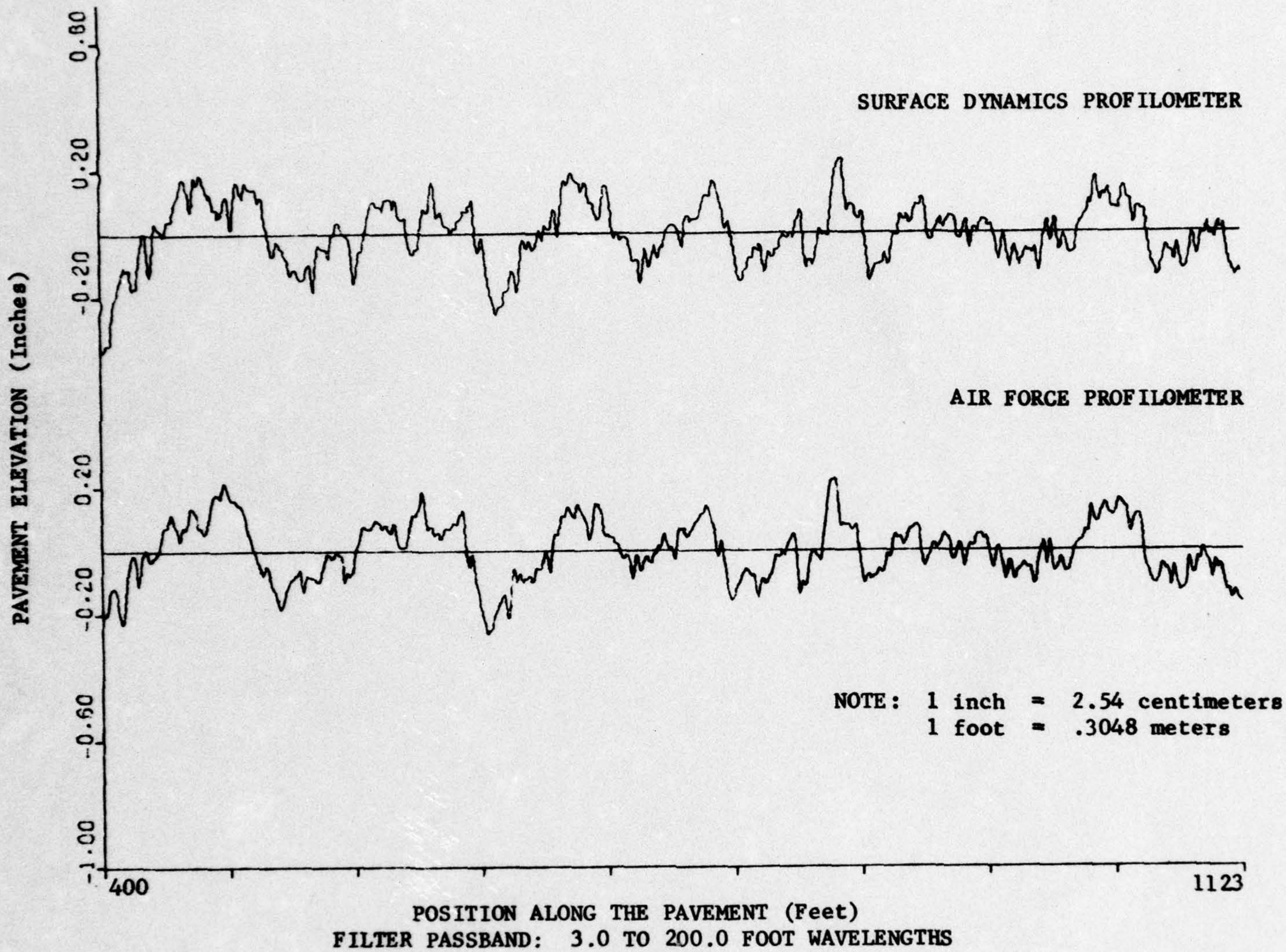


Fig A2.2a. Runway 17 Right, Section A, Left-of-Center, File 1.

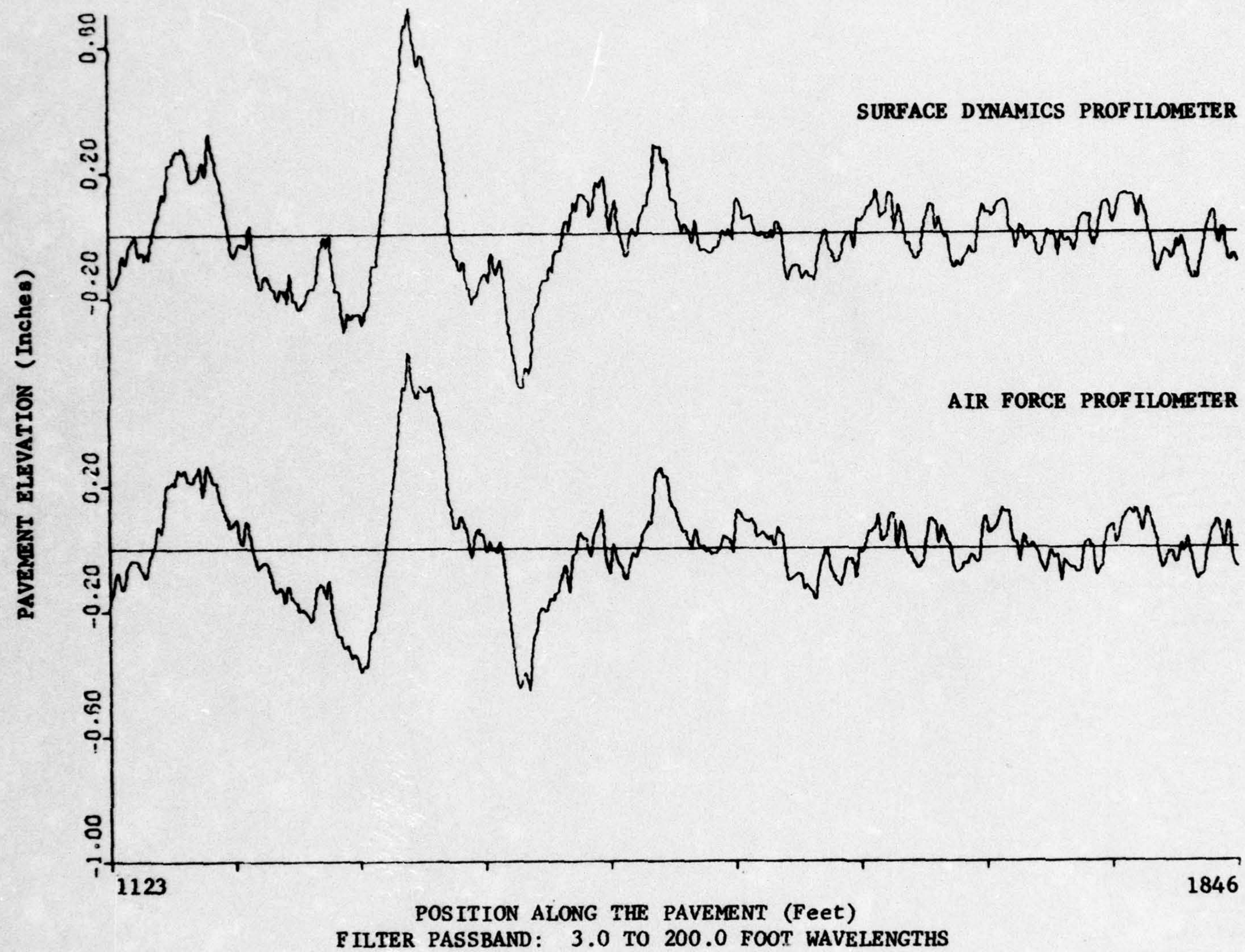


Fig A2.2b. Runway 17 Right, Section A, Left-of-Center, File 1.

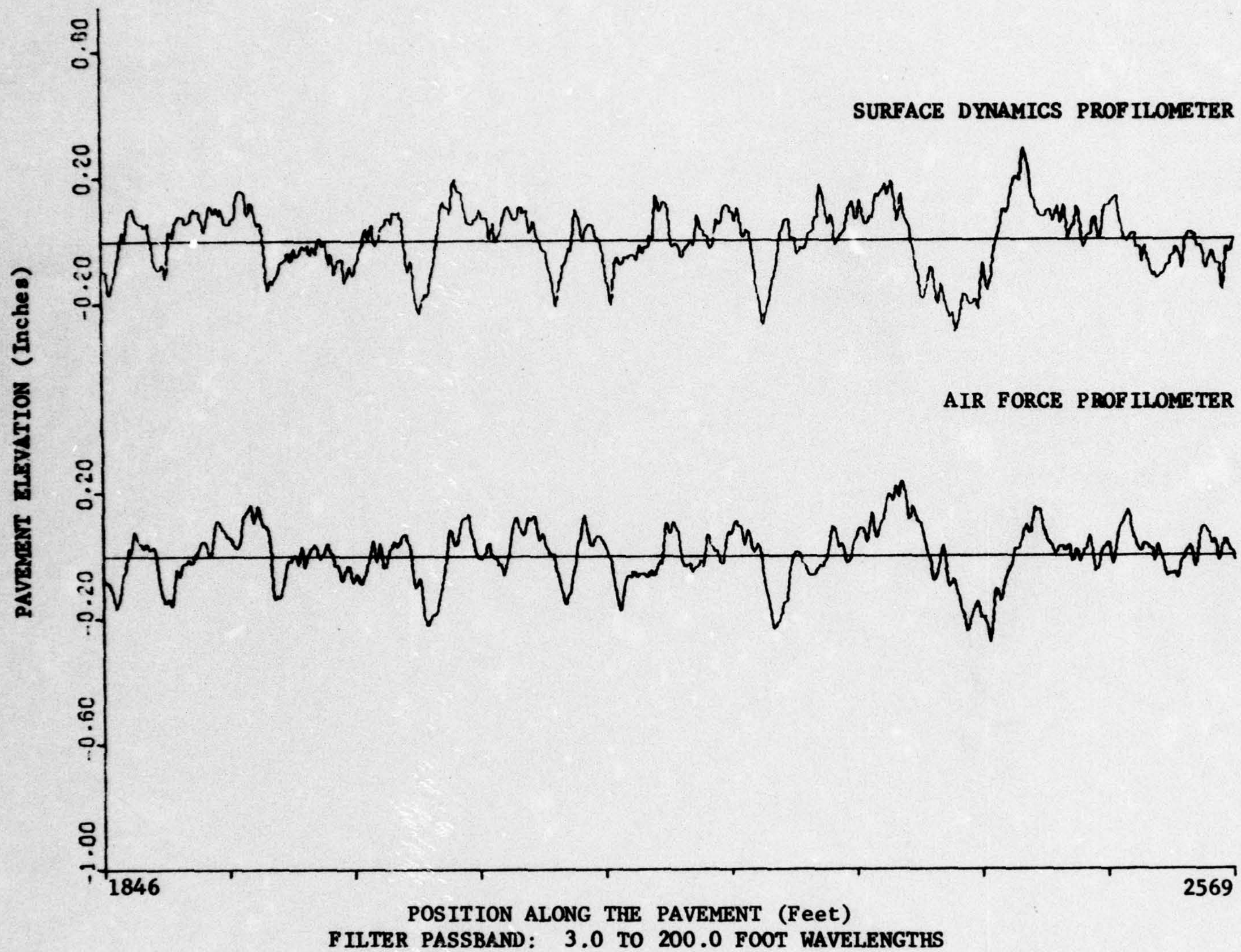


Fig A2.2c. Runway 17 Right, Section A, Left-of-Center, File 1.

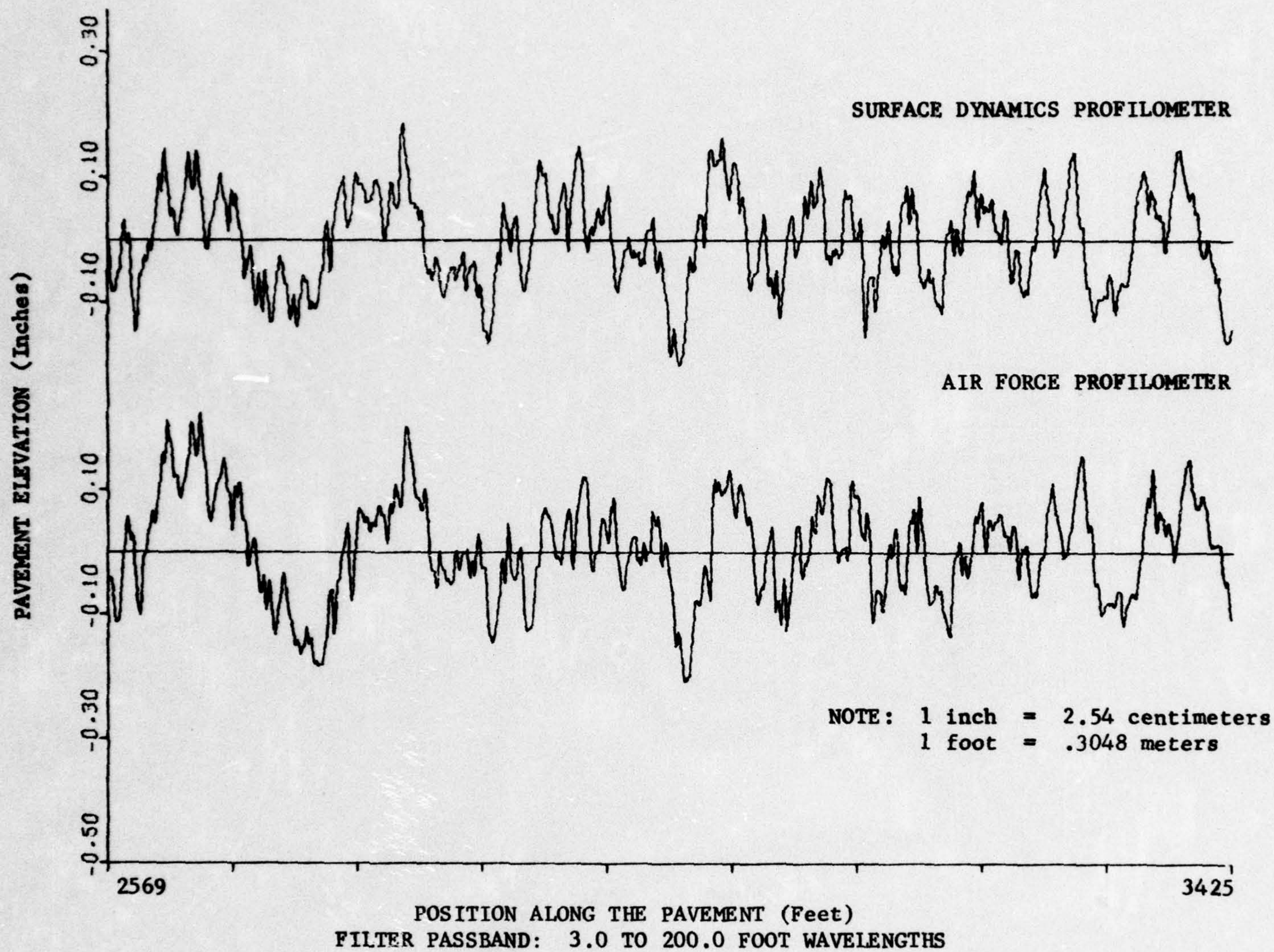


Fig A2.3a. Runway 17 Right, Section B, Right-of-Center, File 1

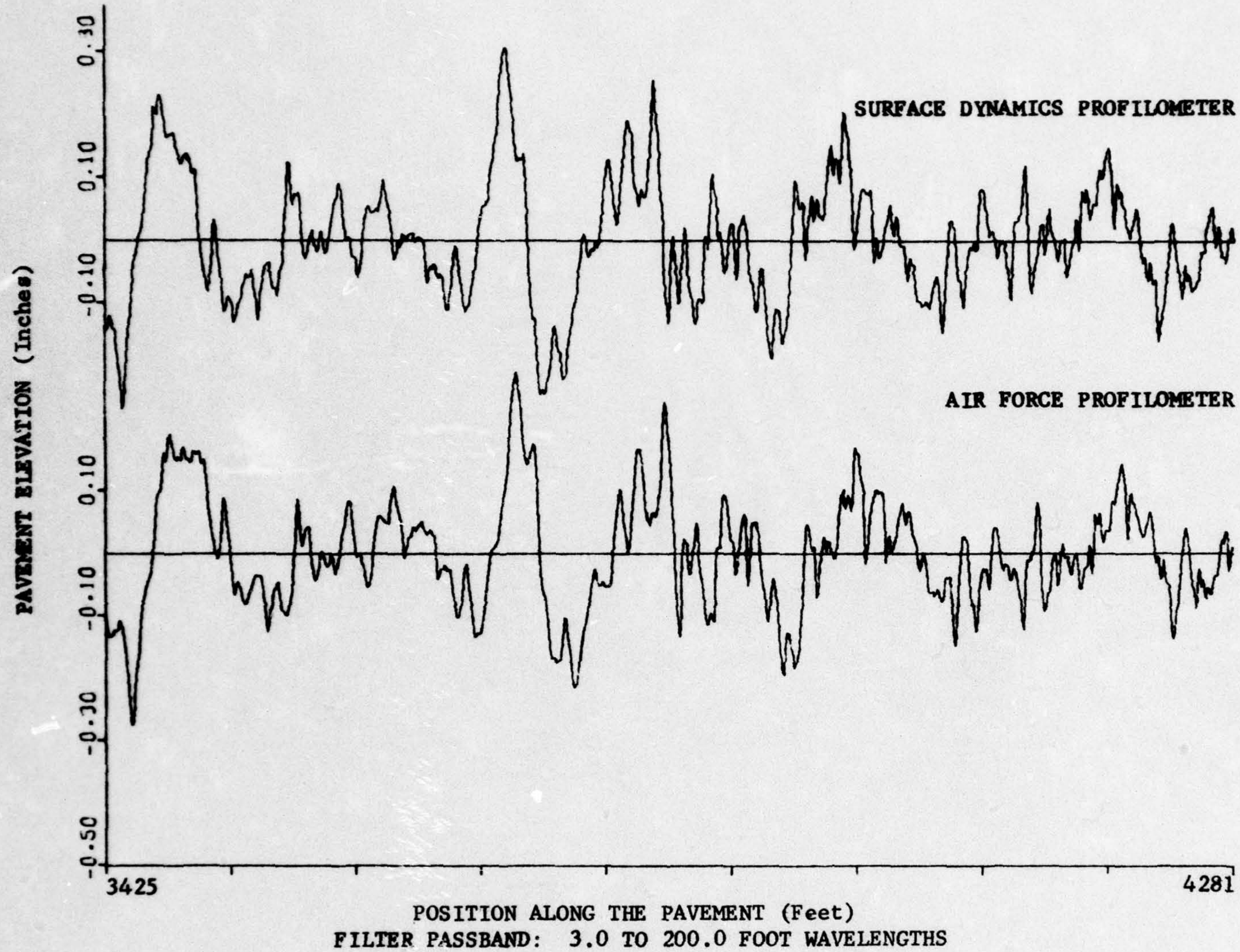


Fig A2.3b. Runway 17 Right, Section B, Right-of-Center, File 1.

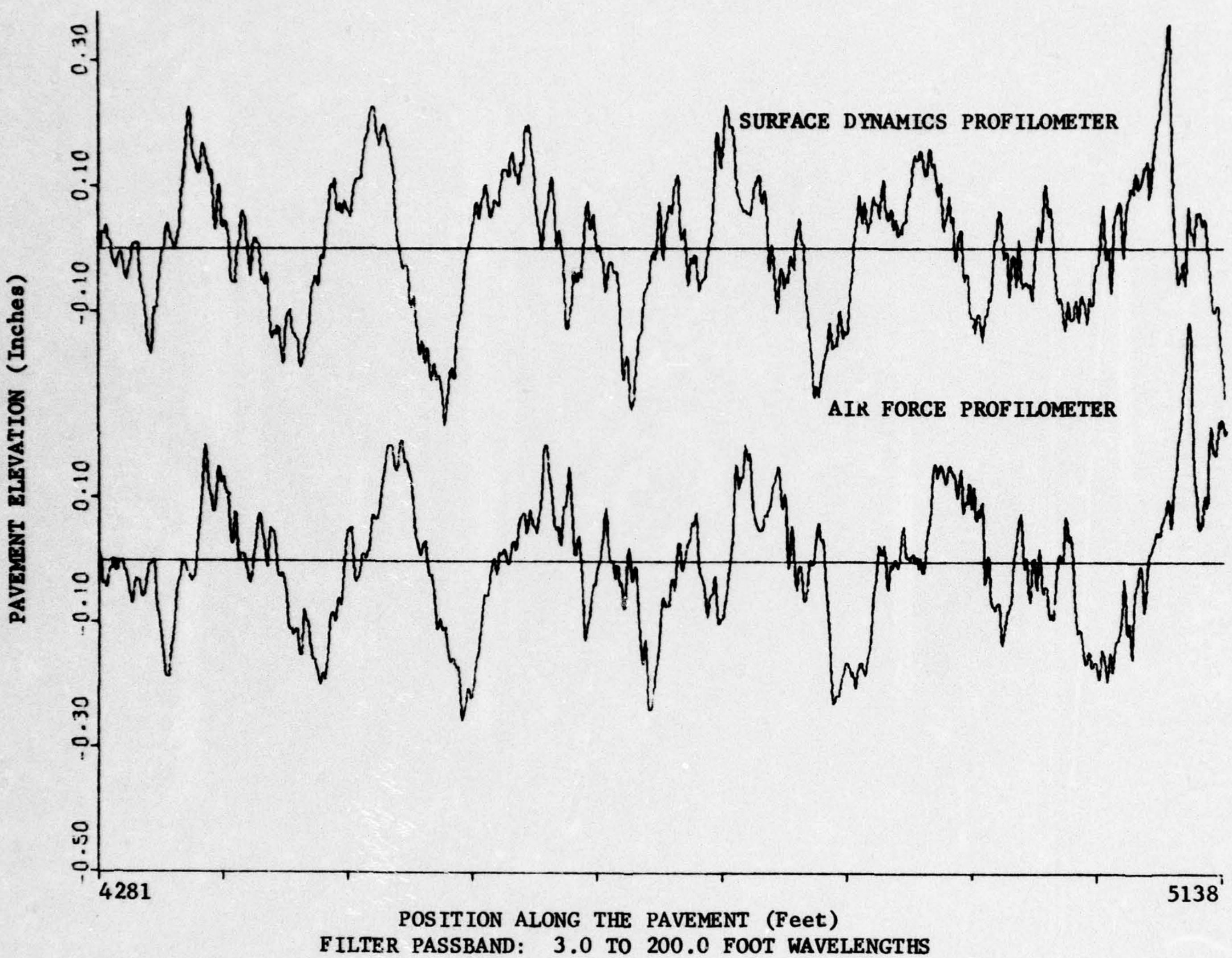


Fig A2.3c. Runway 17 Right, Section B, Right-of-Center, File 1.

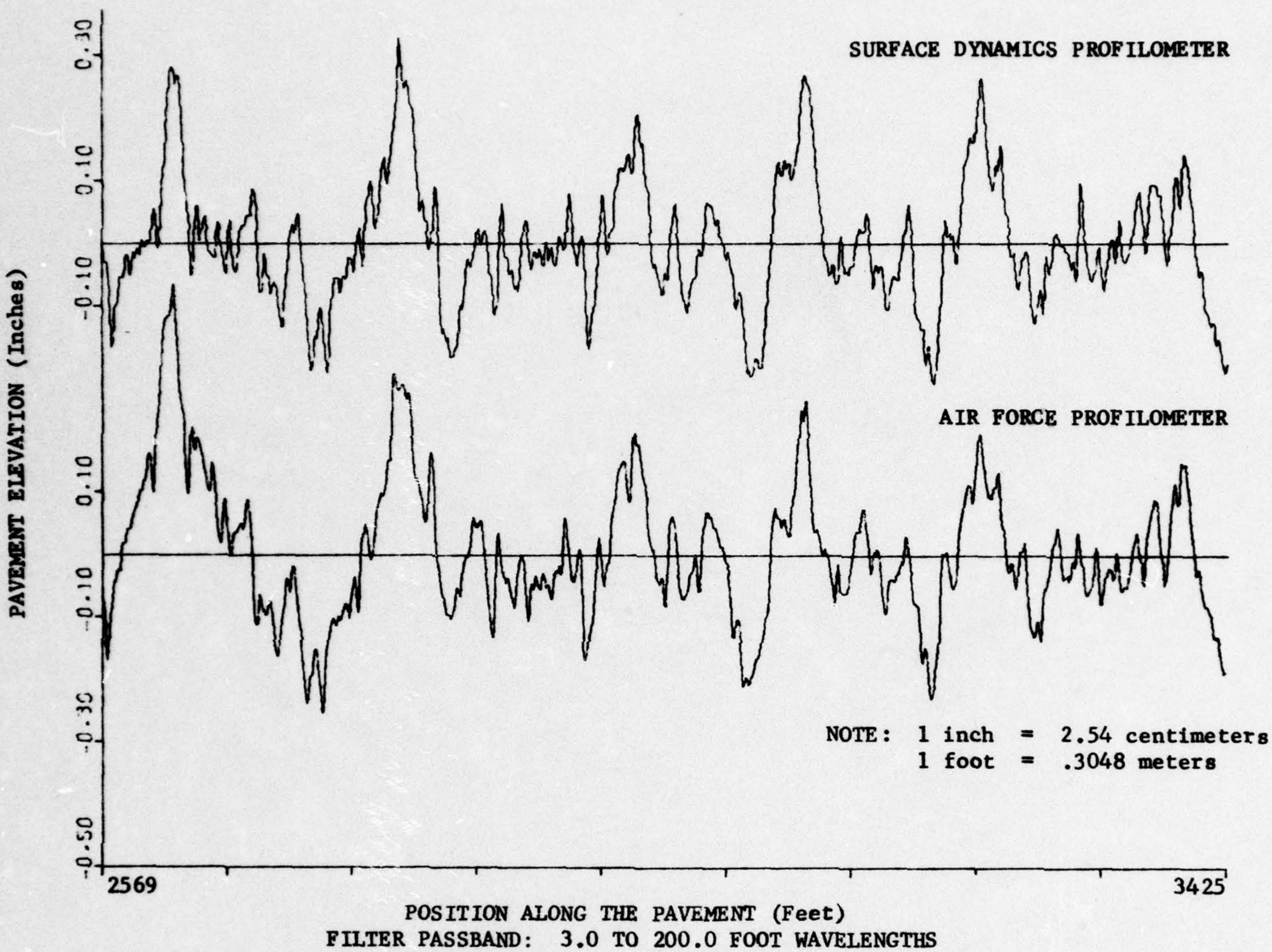


Fig A2.4a. Runway 17 Right, Section B, Left-of-Center, File 1.

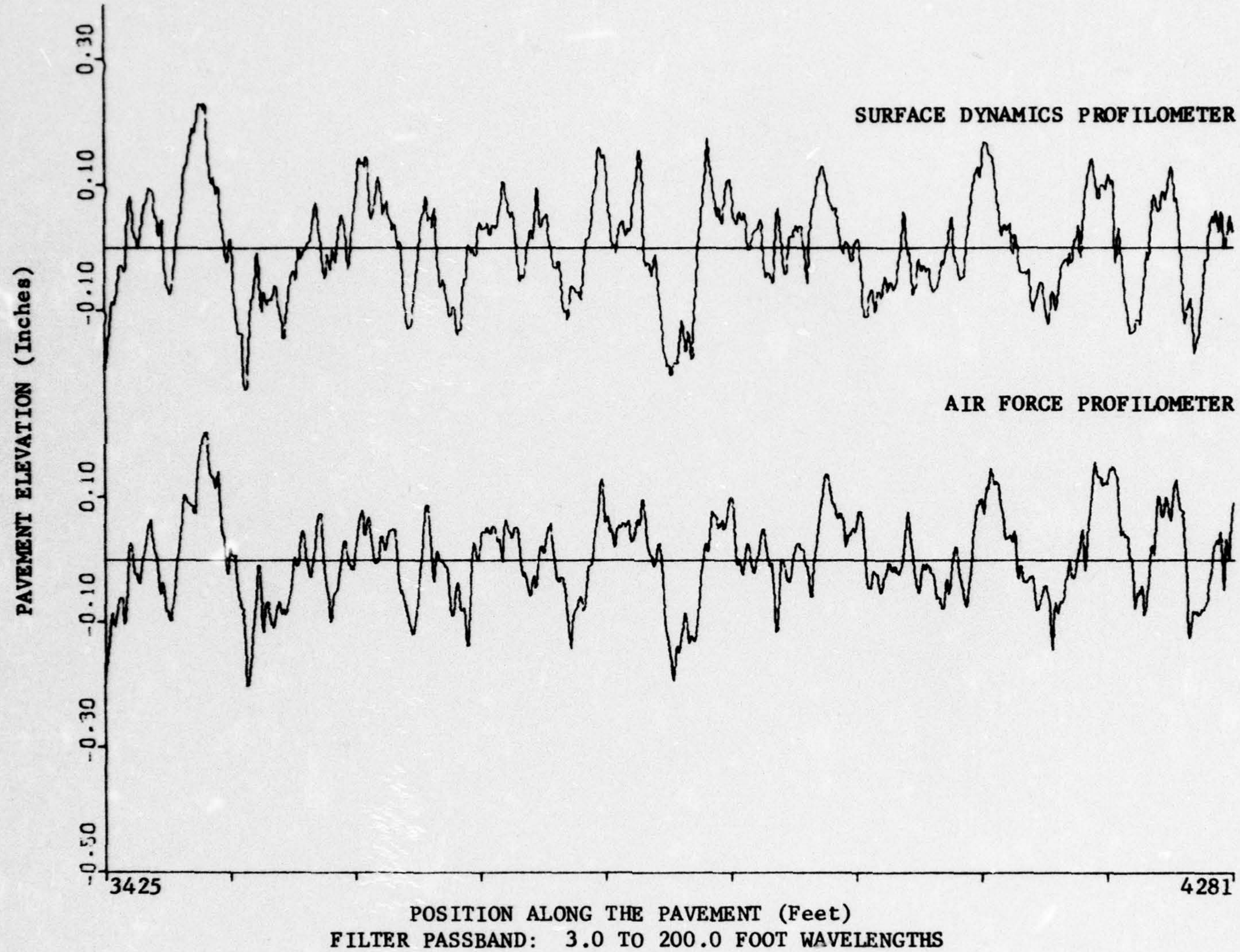


Fig A2.4b. Runway 17 Right, Section B, Left-of-Center, File 1.

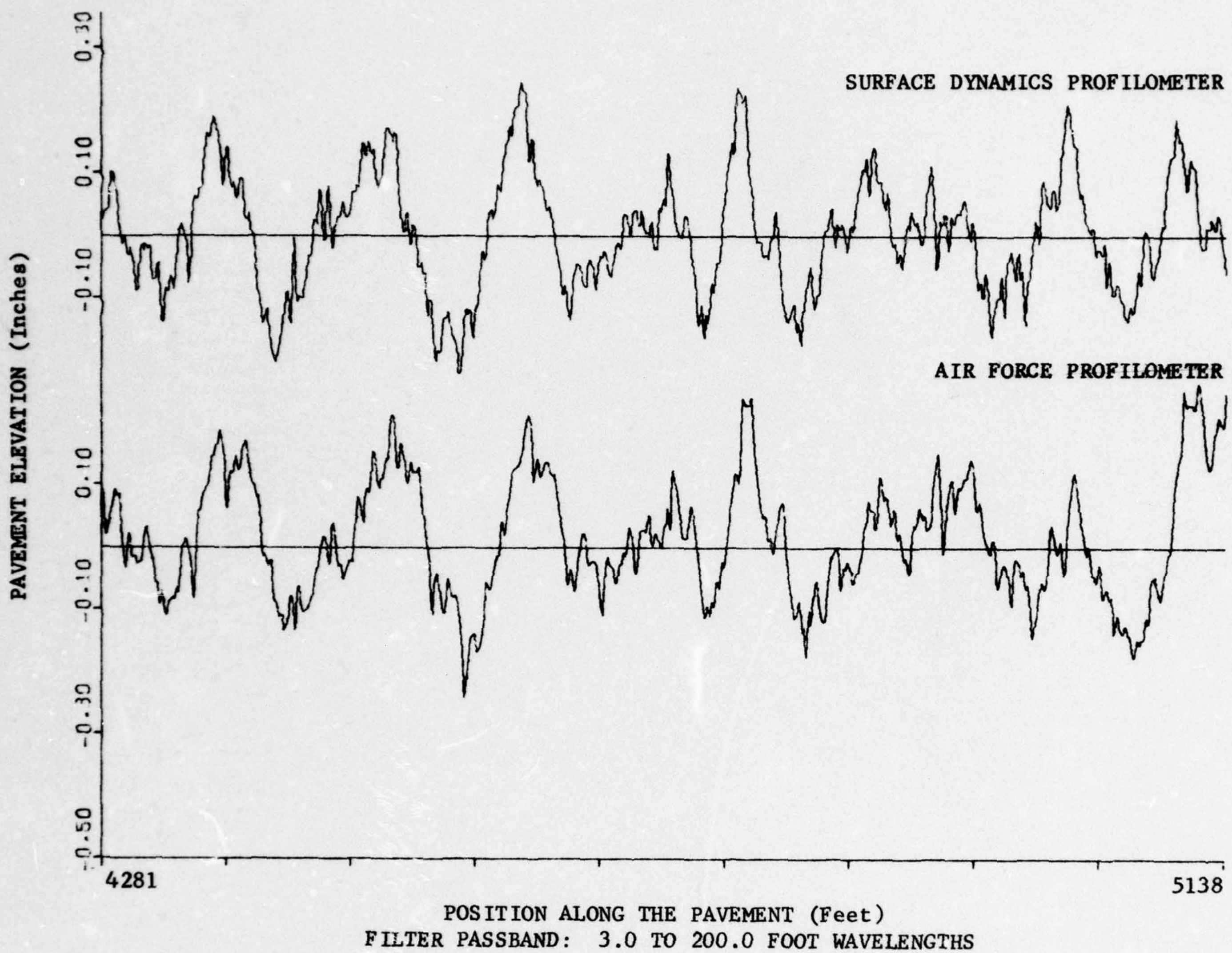


Fig A2.4c. Runway 17 Right, Section B, Left-of-Center, File 1.

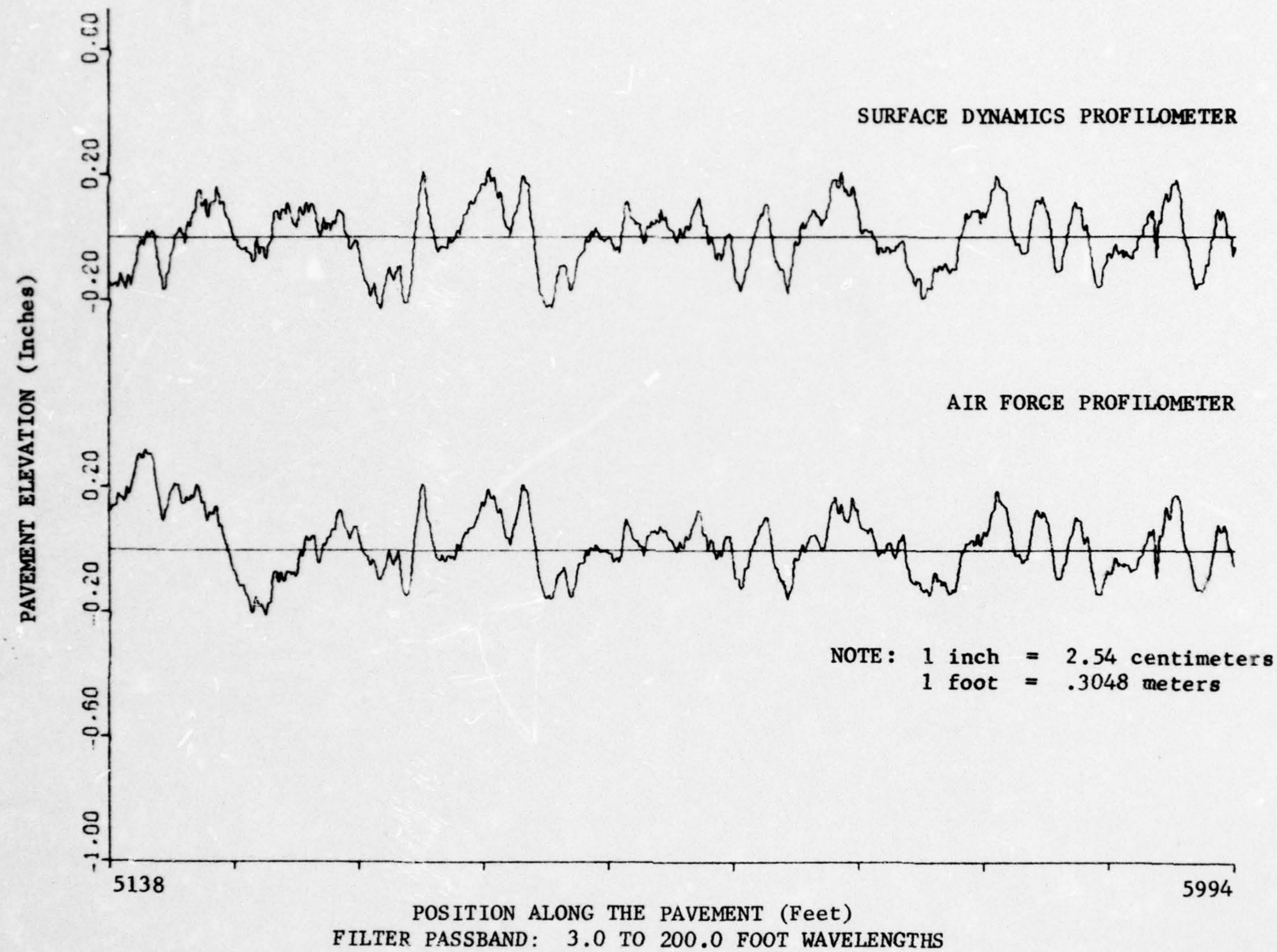


Fig A2.5a. Runway 17 Right, Section C, Right-of-Center, File 1

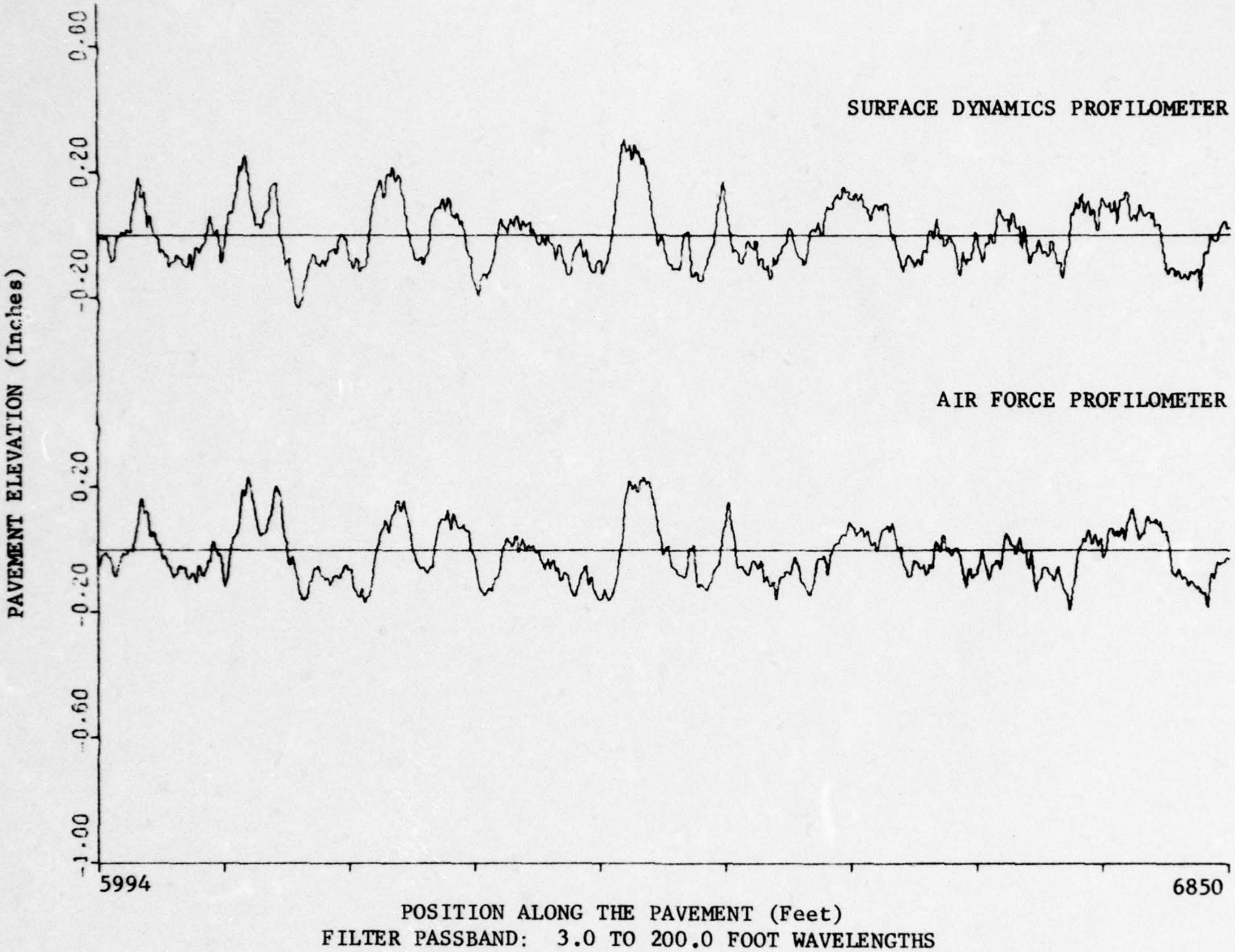


Fig A2.5b. Runway 17 Right, Section C, Right-of-Center, File 1.

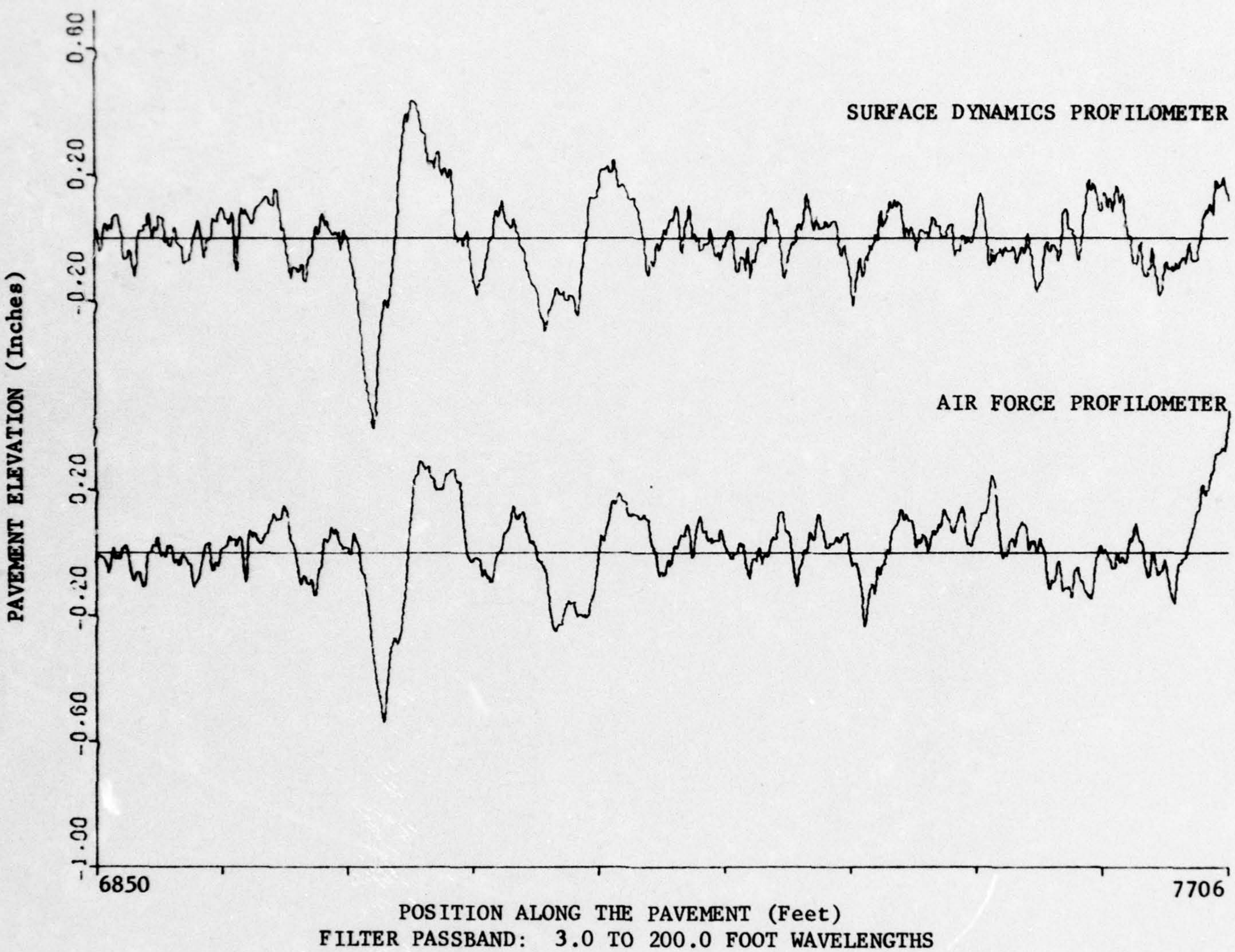


Fig A2.5c. Runway 17 Right, Section C, Right-of-Center, File 1.

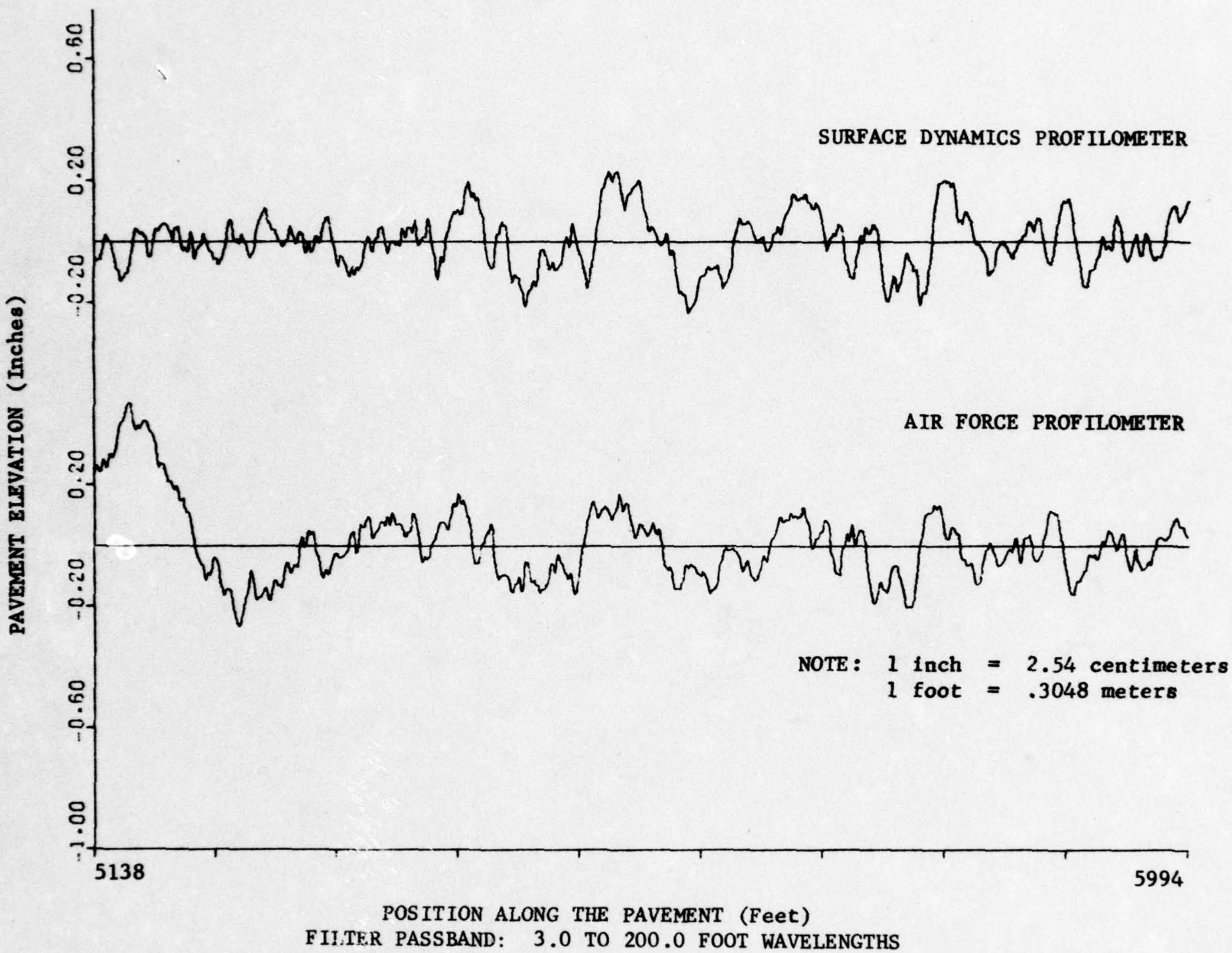


Fig A2.6a. Runway 17 Right, Section C, Left-of-Center, File 1.

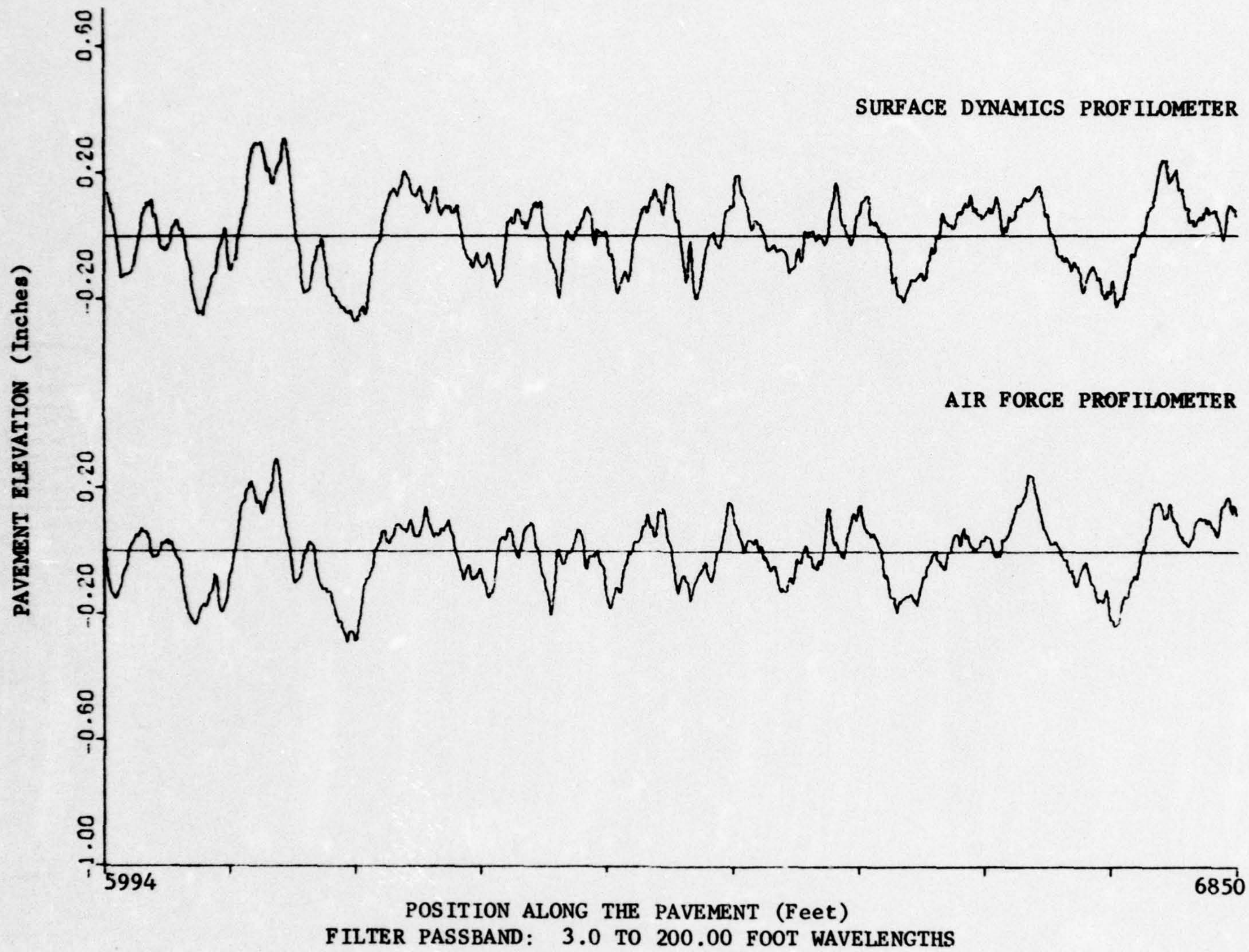


Fig A2.6b. Runway 17 Right, Section C, Left-of-Center, File 1.

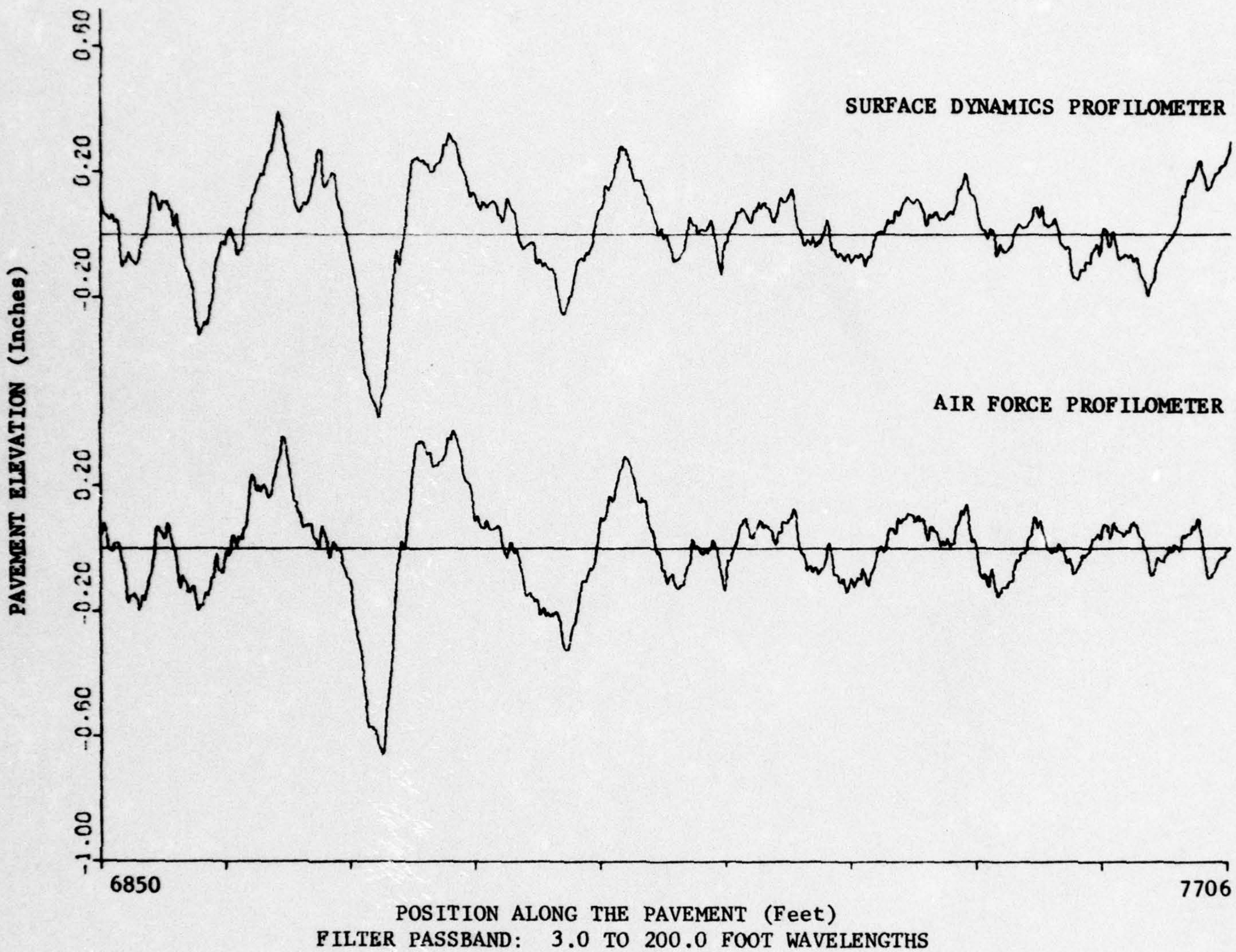


Fig A2.6c. Runway 17 Right, Section C, Left-of-Center, File 1.

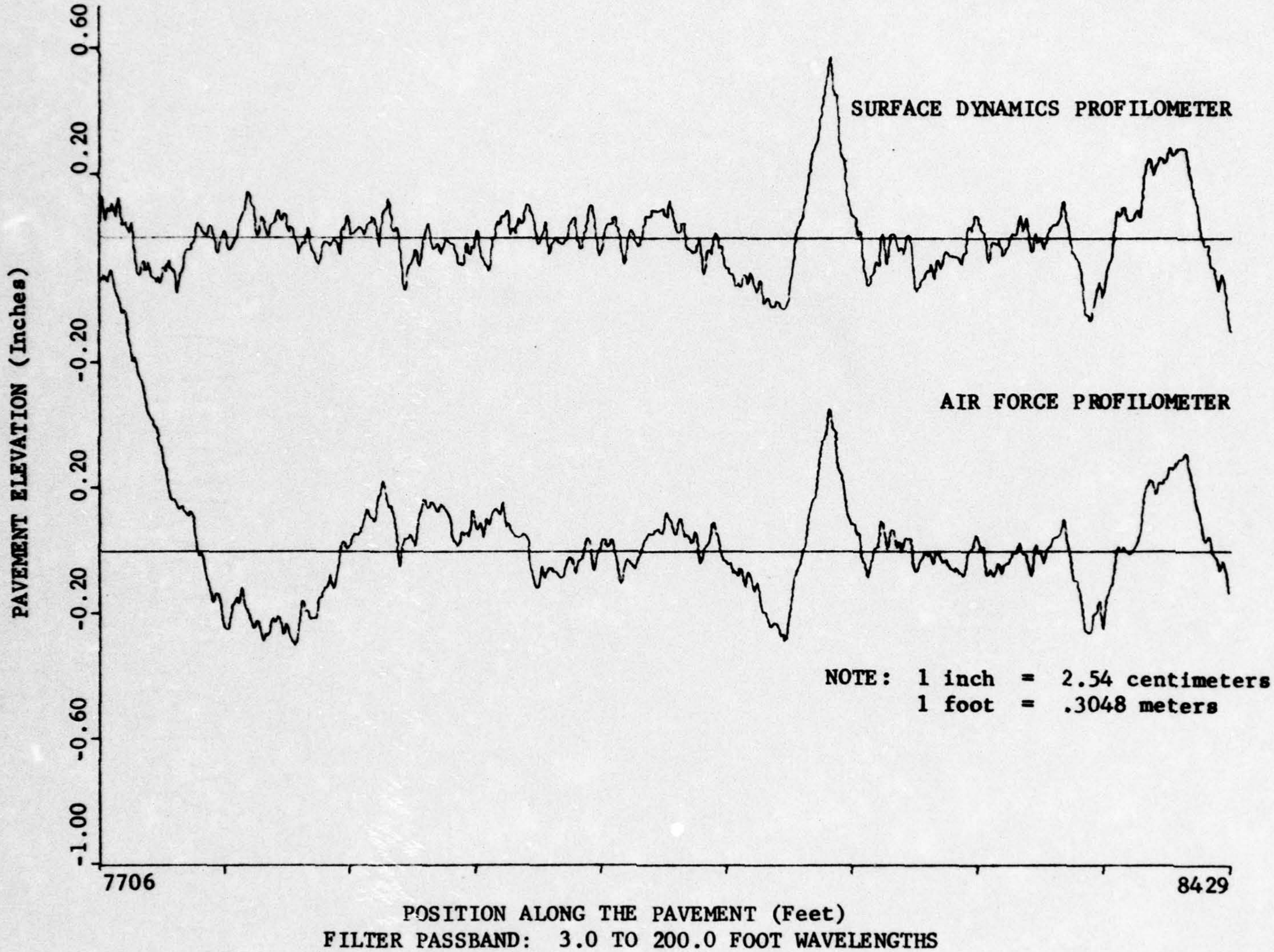


Fig A2.7a. Runway 17 Right, Section D, Right-of-Center, File 1.

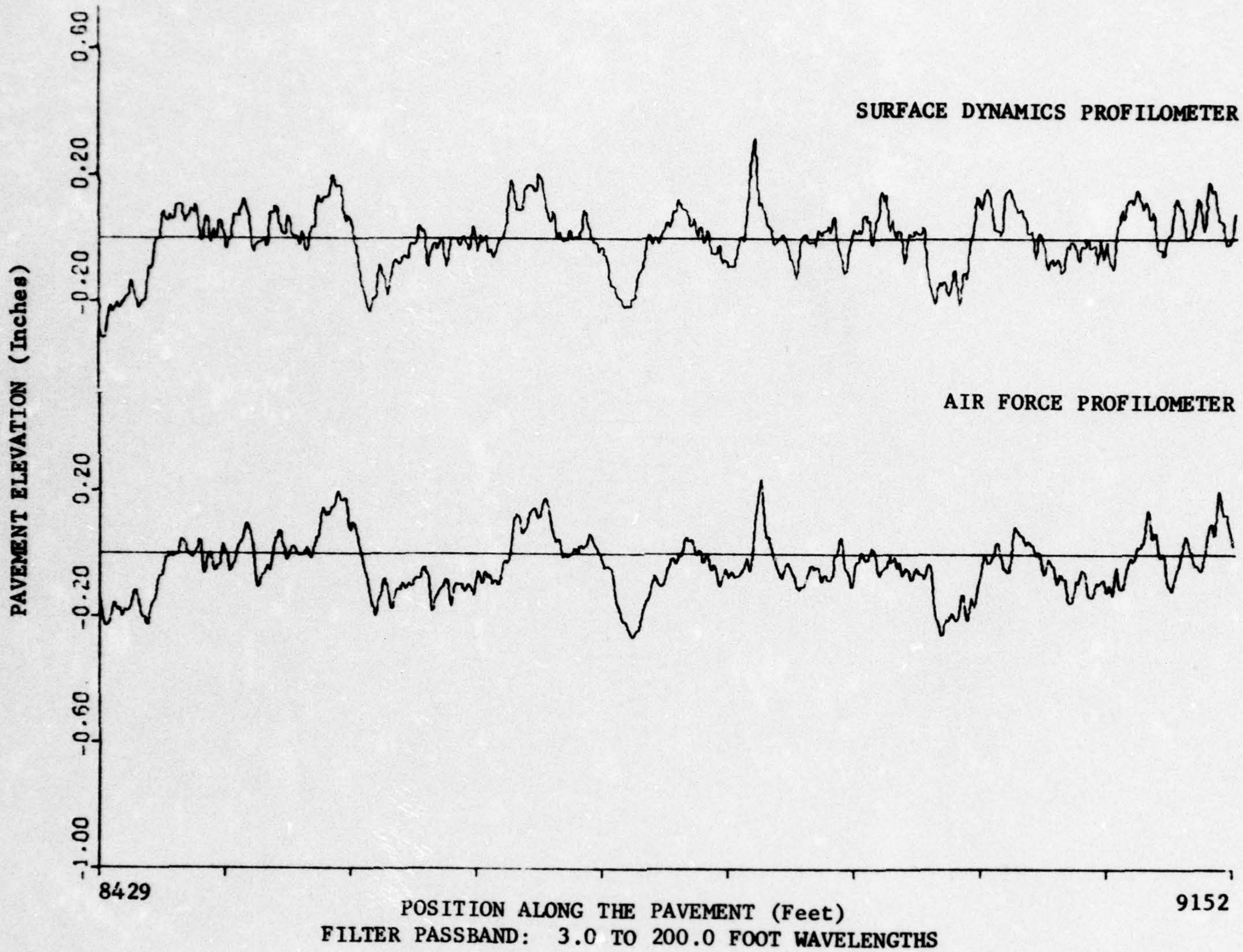


Fig A2.7b. Runway 17, Right, Section D, Right-of-Center, File 1.

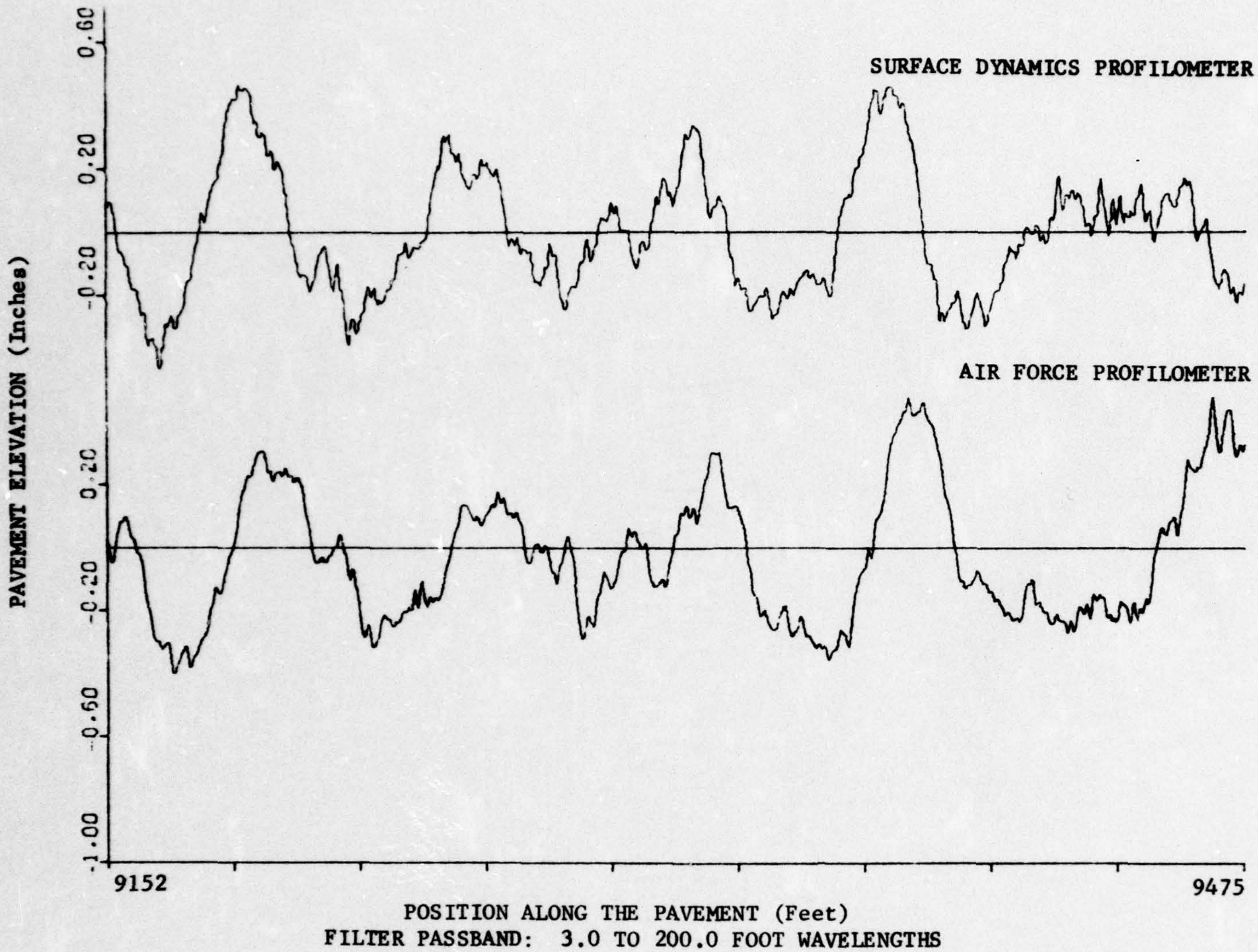
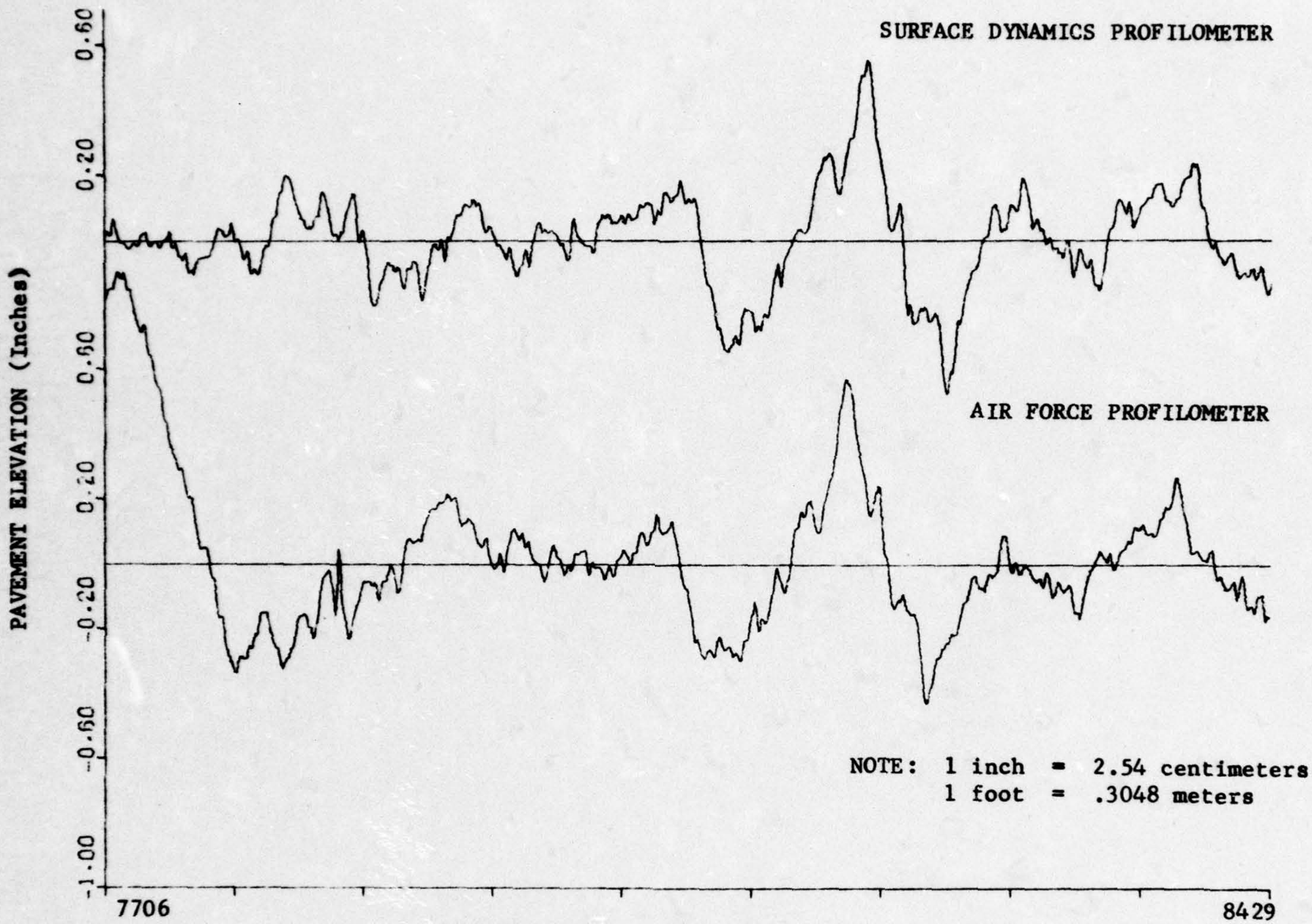
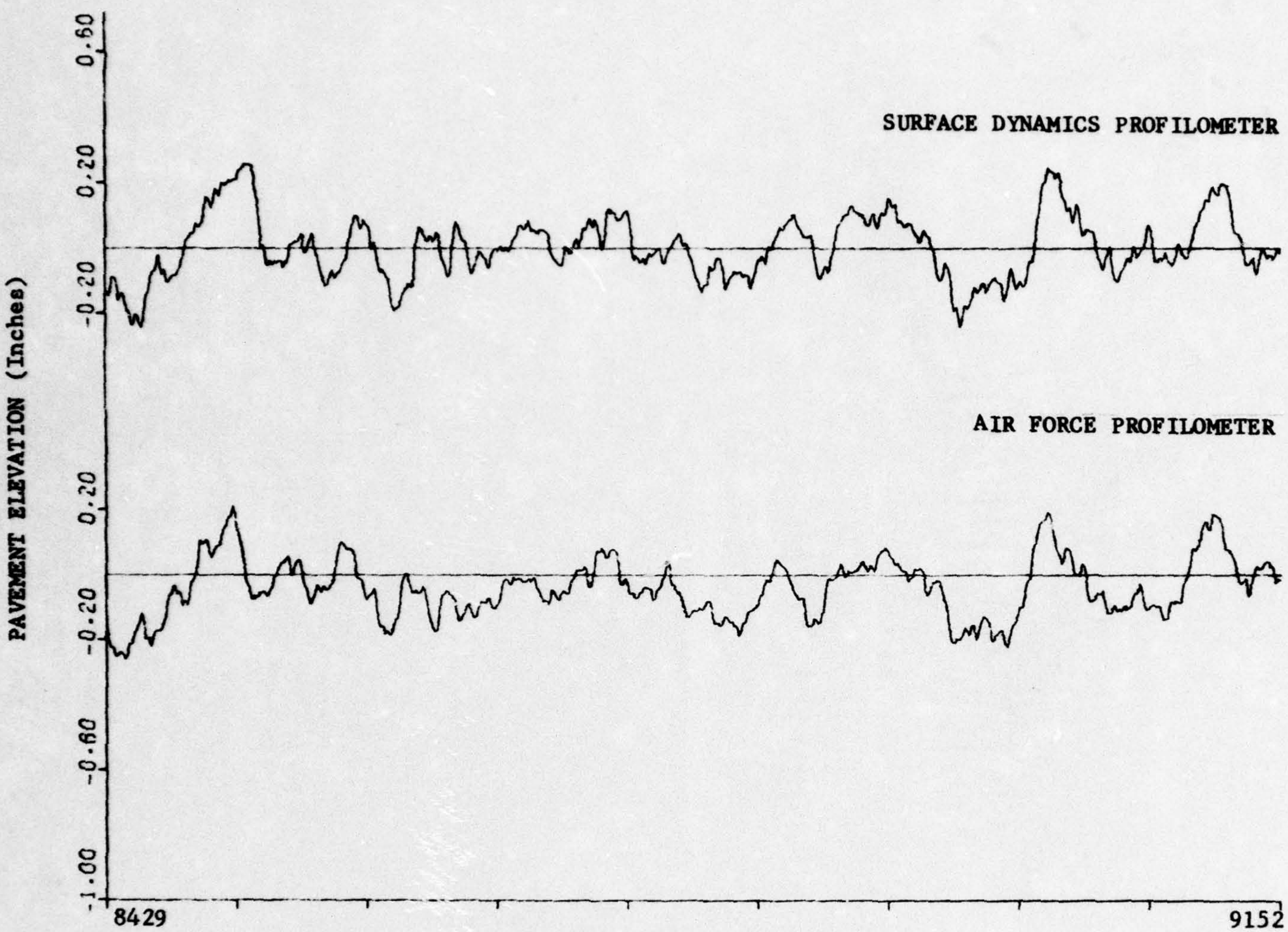


Fig A2.7c. Runway 17 Right, Section D, Right-of-Center, File 1.



POSITION ALONG THE PAVEMENT (Feet)
FILTER PASSBAND: 3.0 TO 200.0 FOOT WAVELENGTHS

Fig A2.8a. Runway 17 Right, Section D, Left-of-Center, File 1.



POSITION ALONG THE PAVEMENT (Feet)
FILTER PASSBAND: 3.0 TO 200.0 FOOT WAVELENGTHS

Fig A2.8b. Runway 17, Right, Section D, Left-of-Center, File 1.

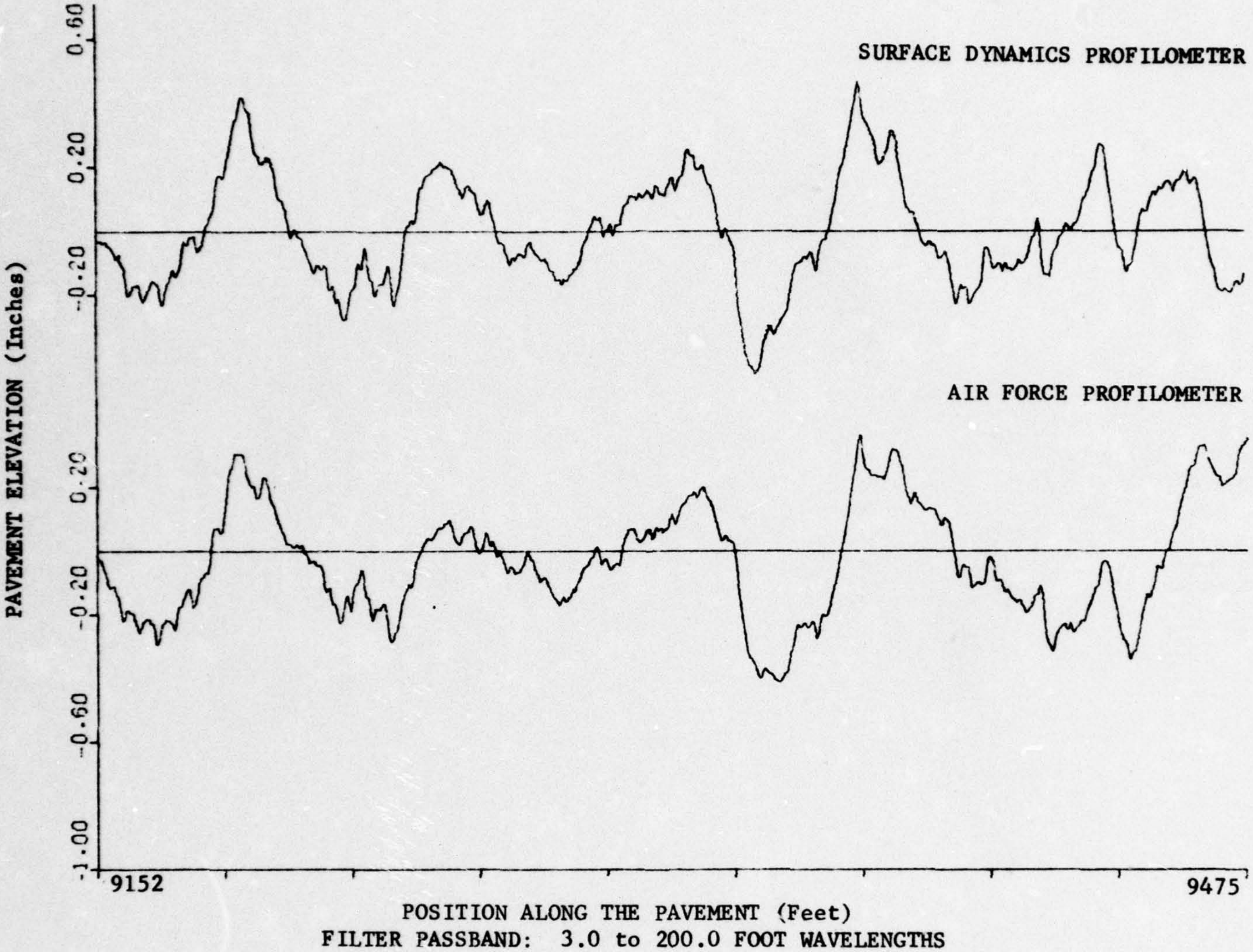


Fig A2.8c. Runway 17, Right, Section D, Left-of-Center, File 1.

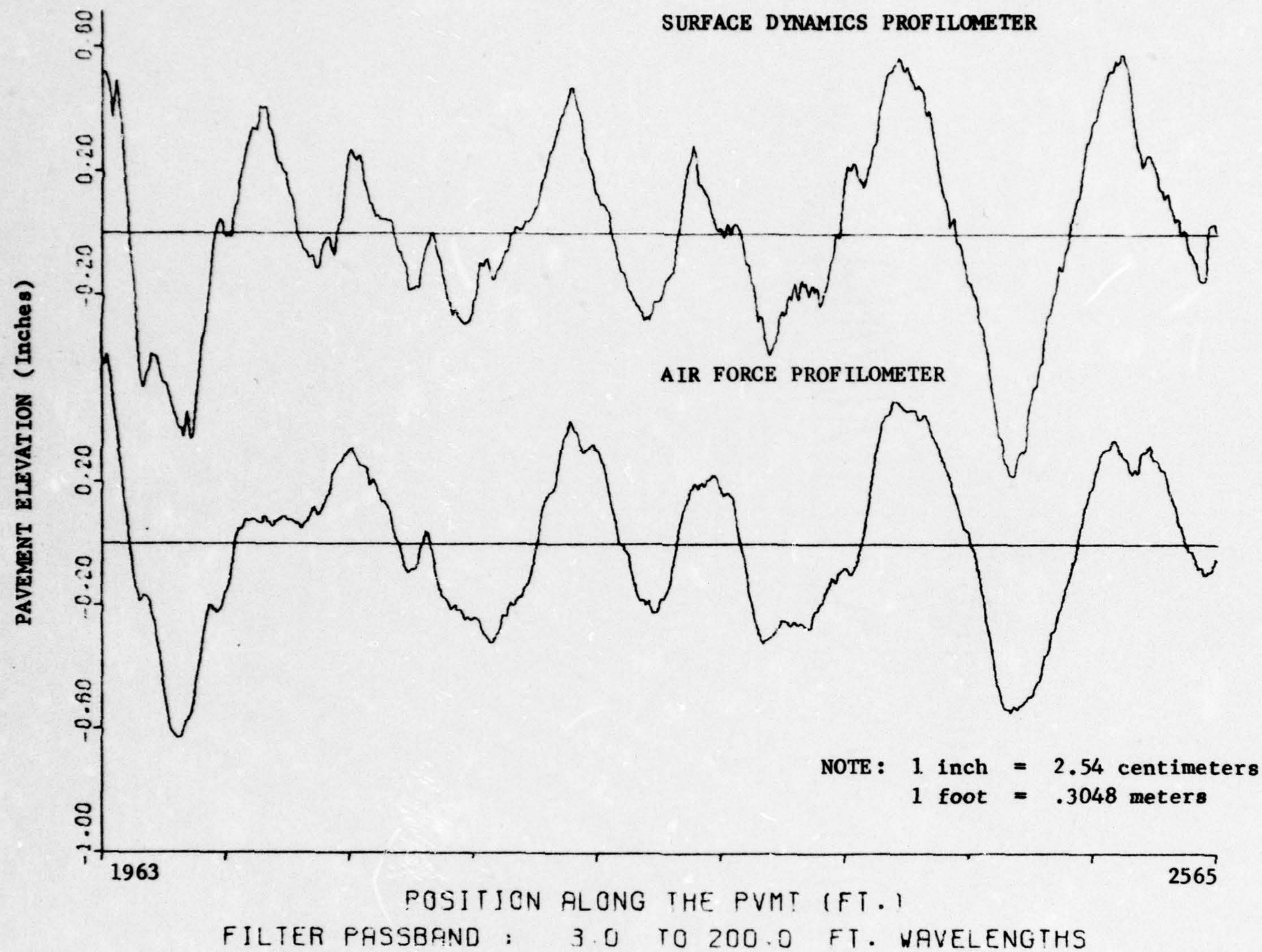


Fig A2.9a. Runway 35 Right, Centerline, Section A, File 1.

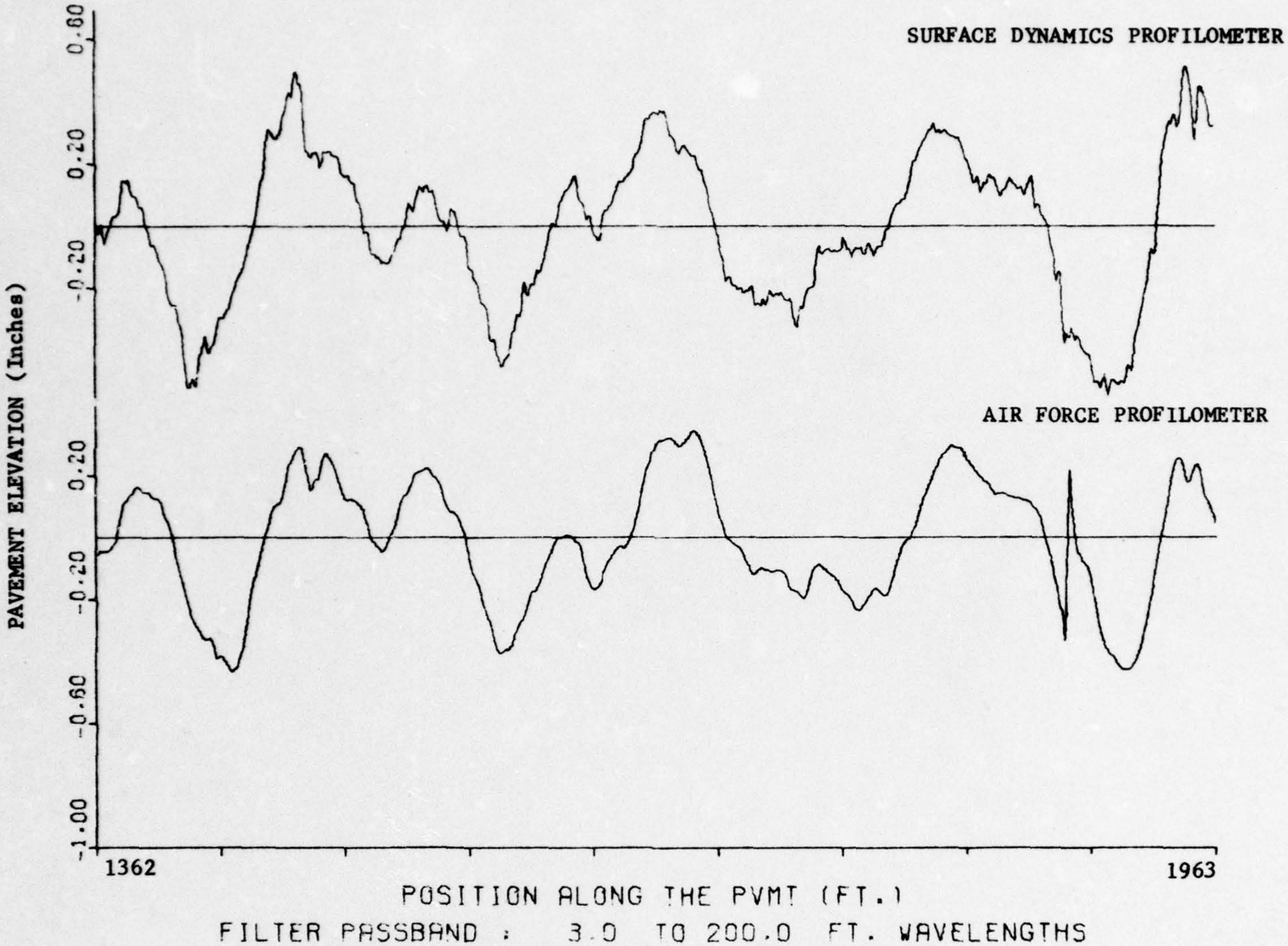


Fig A2.9b. Runway 35 Right, Centerline, Section A, File 1.

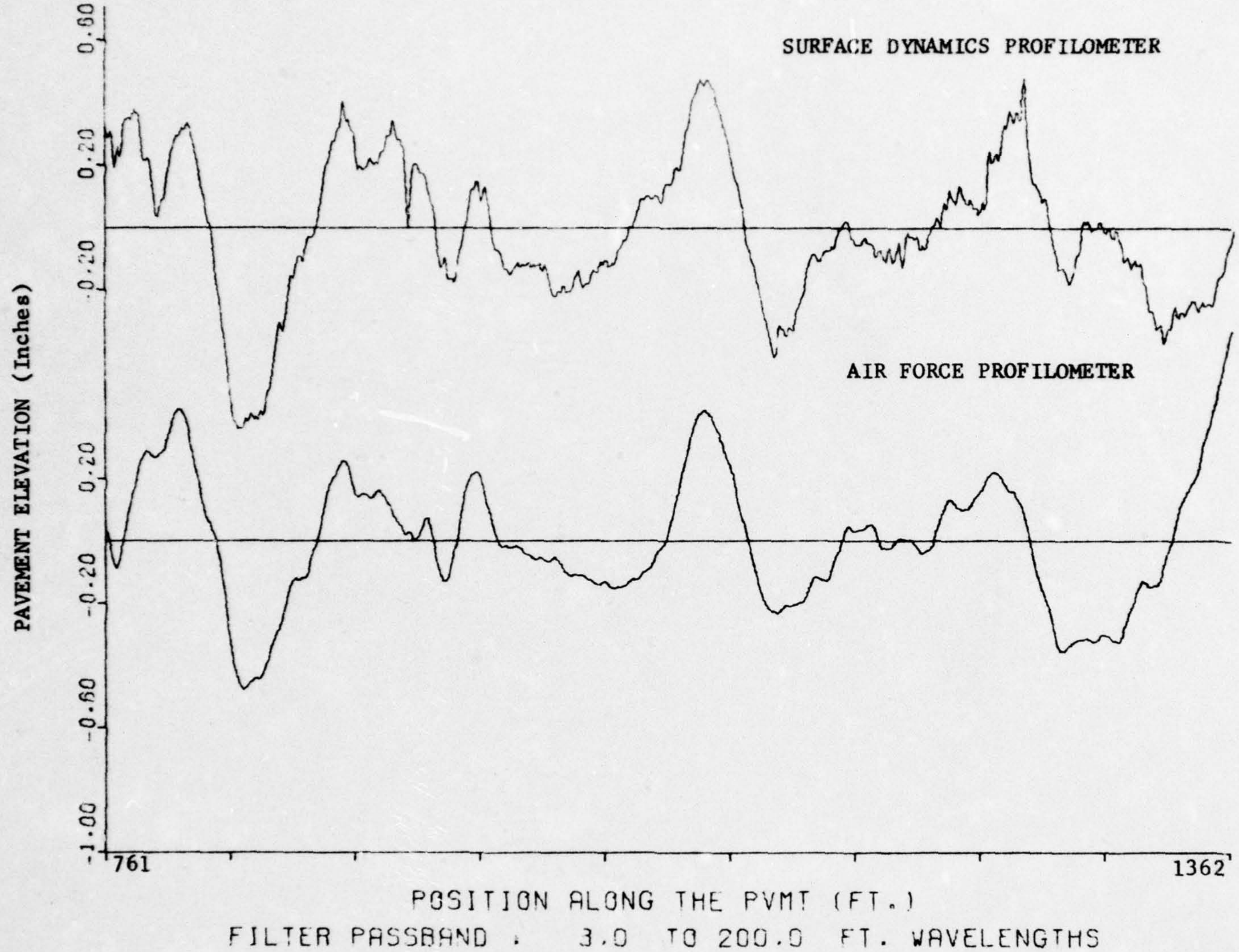


Fig A2.9c. Runway 35 Right, Centerline, Section A, File 1.

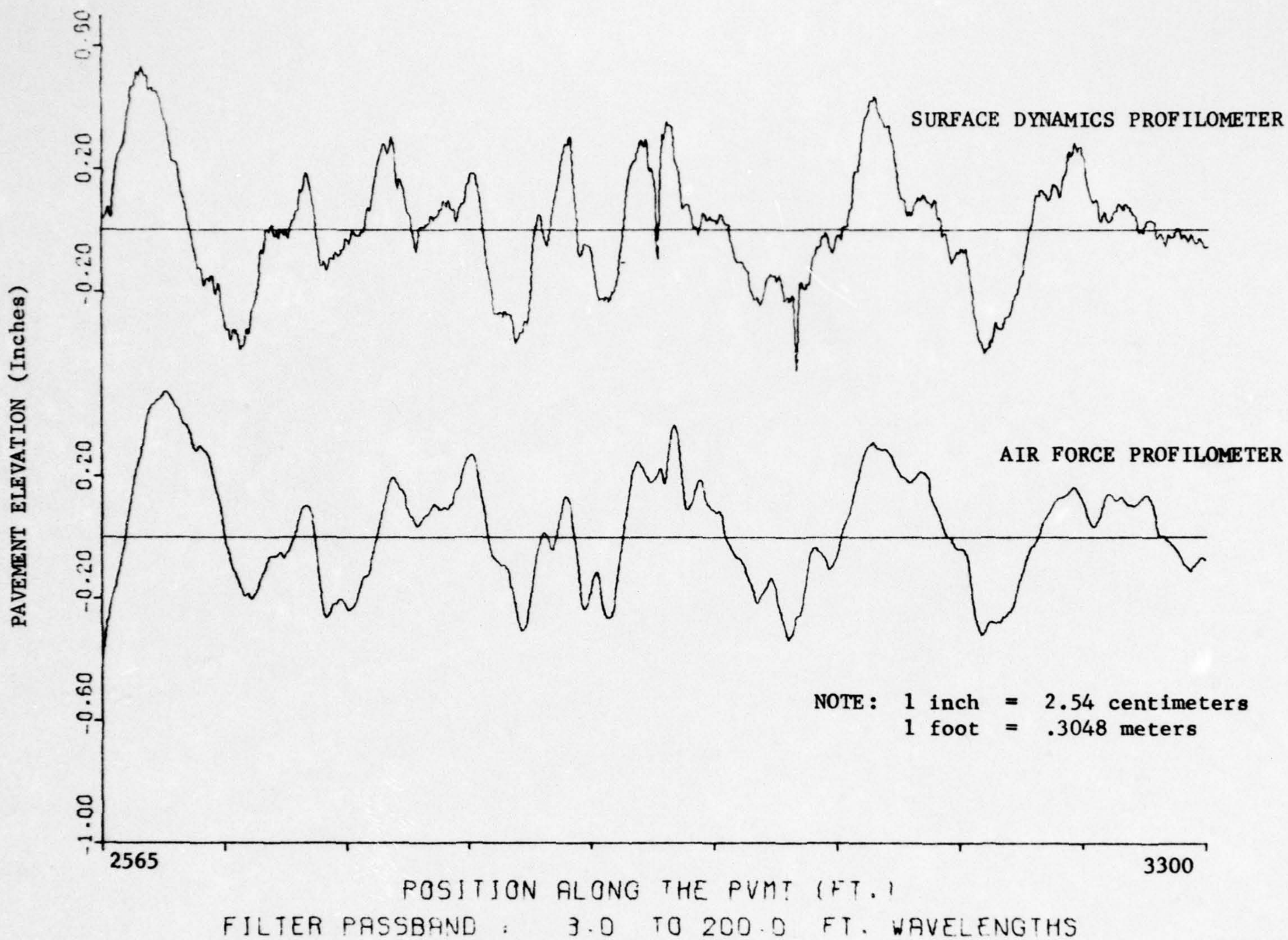


Fig A2.10a. Runway 35 Right, Centerline, Section B, File 1.

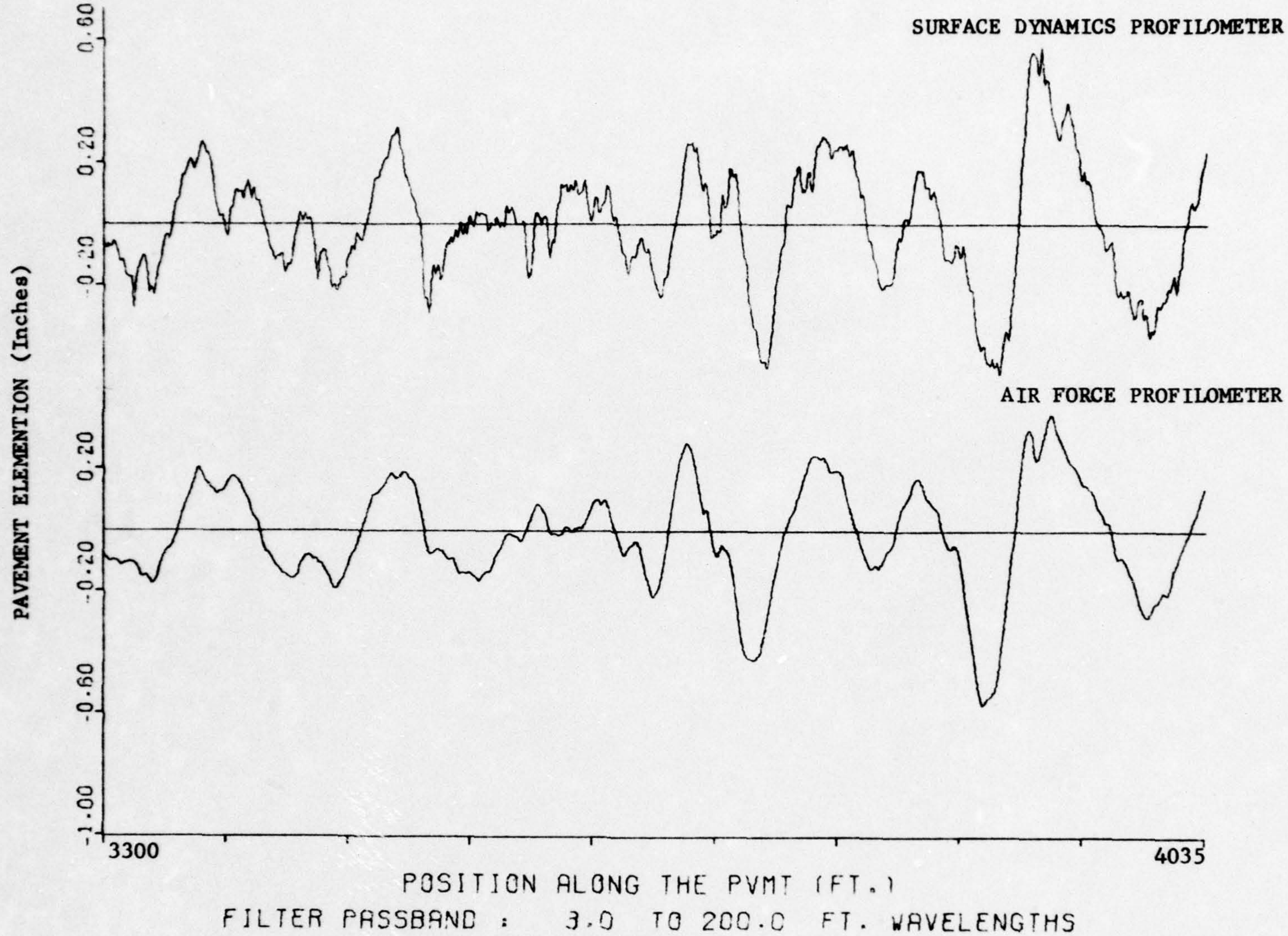


Fig 2.10b. Runway 35 Right, Centerline, Section B, File 1.

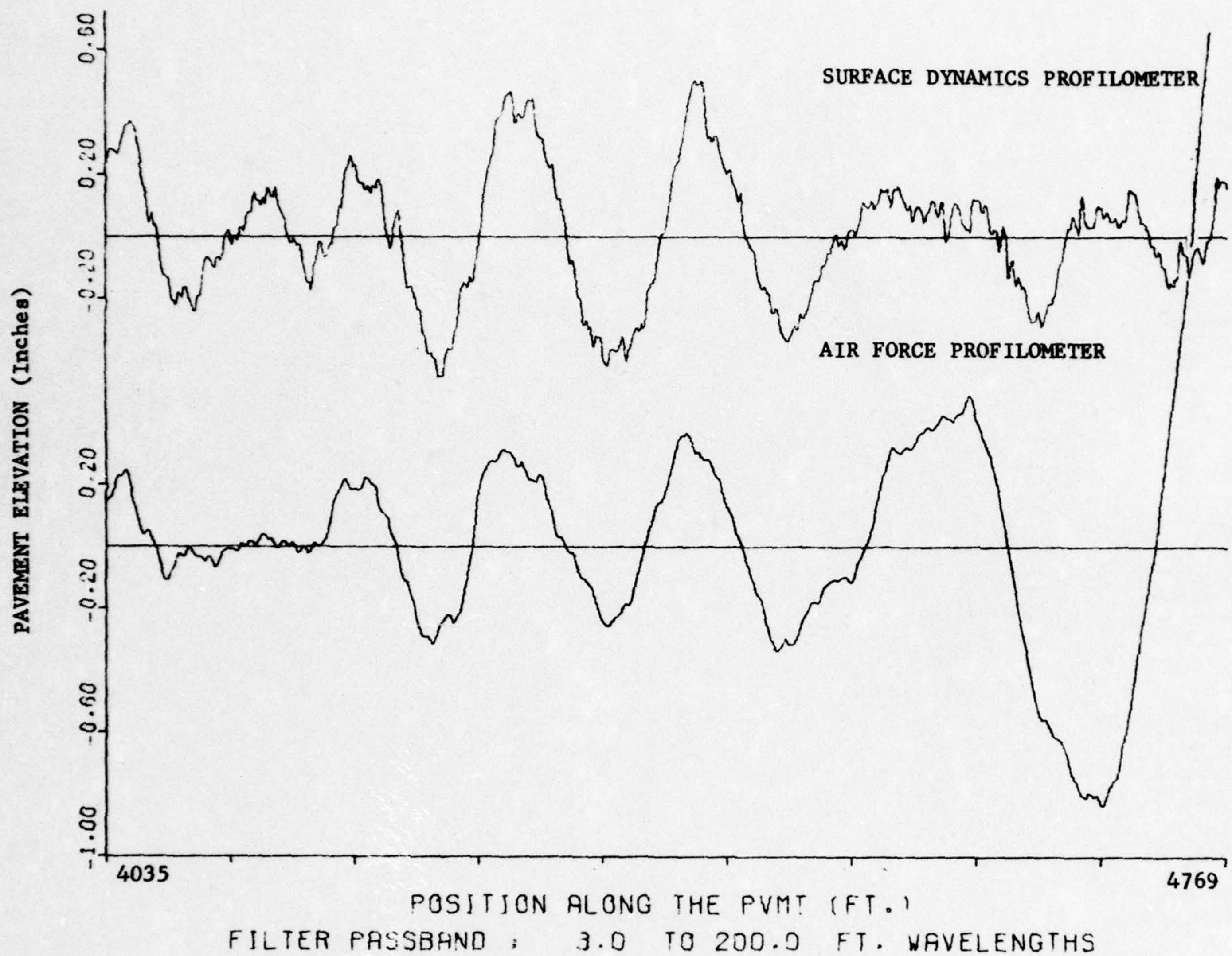


Fig A2.10c. Runway 35 Right, Centerline, Section B, File 1.

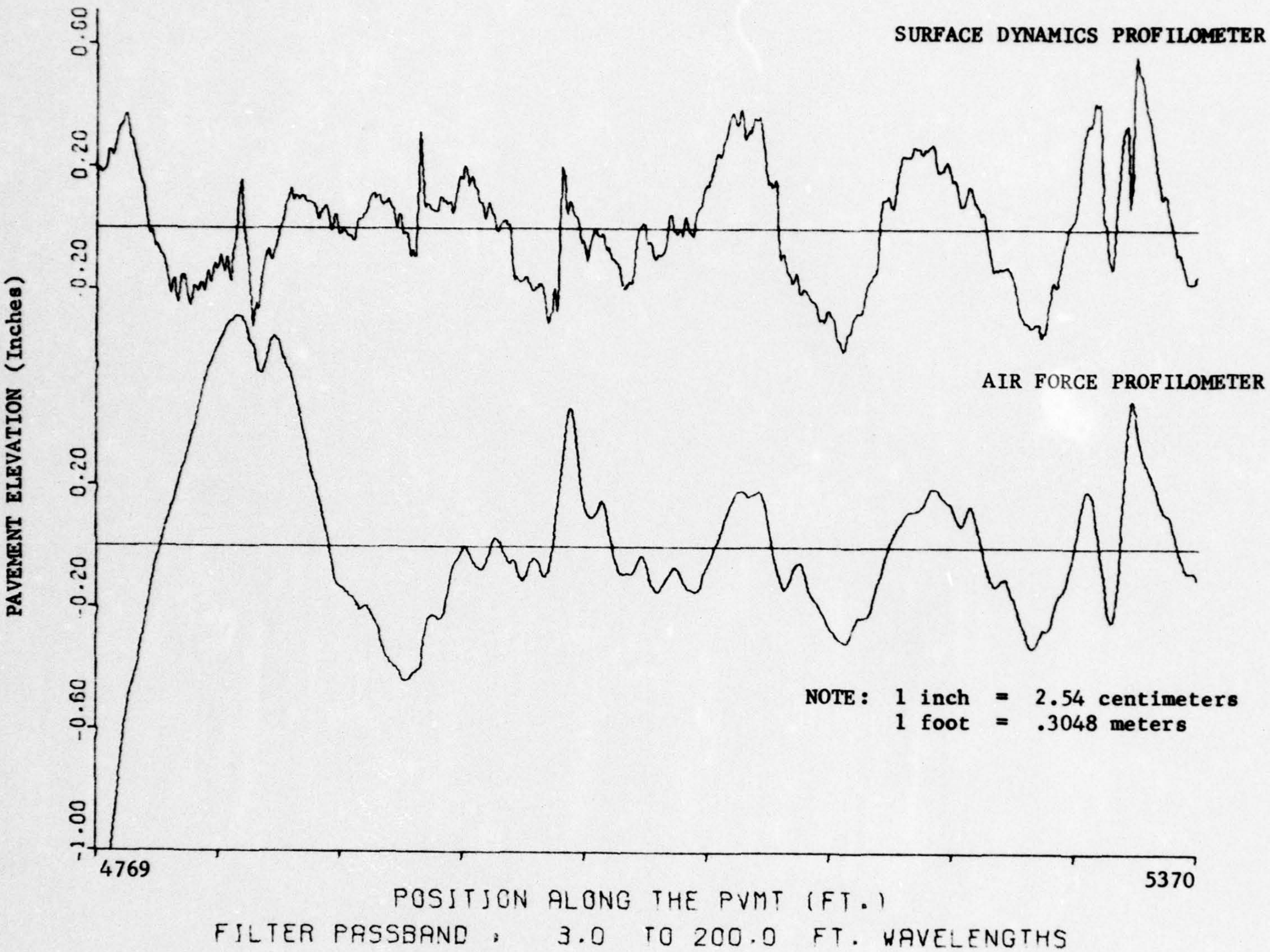


Fig A2.11a. Runway 35 Right, Centerline, Section C, File 1.

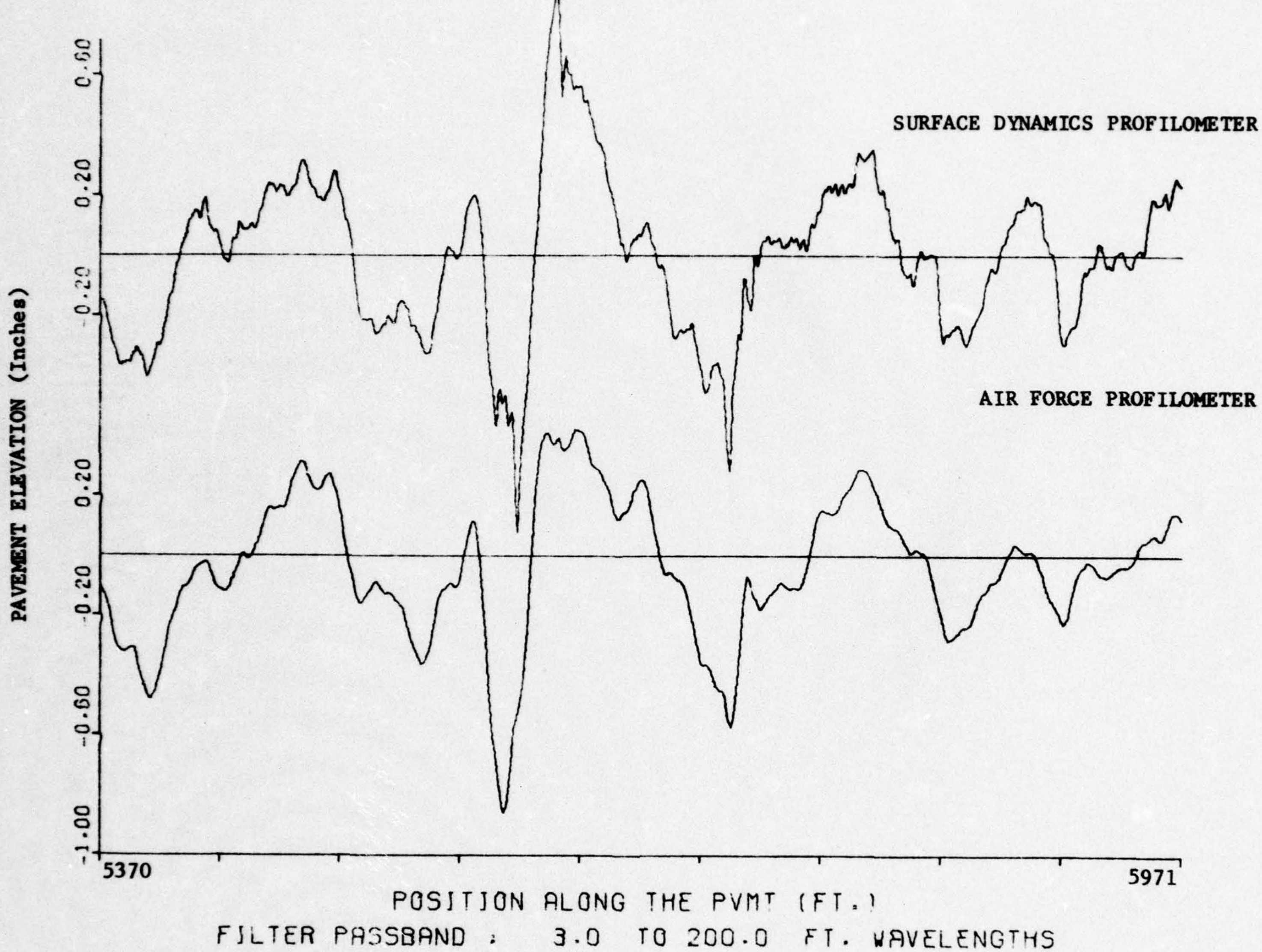


Fig A2.11b. Runway 35 Right, Centerline, Section C, File 1.

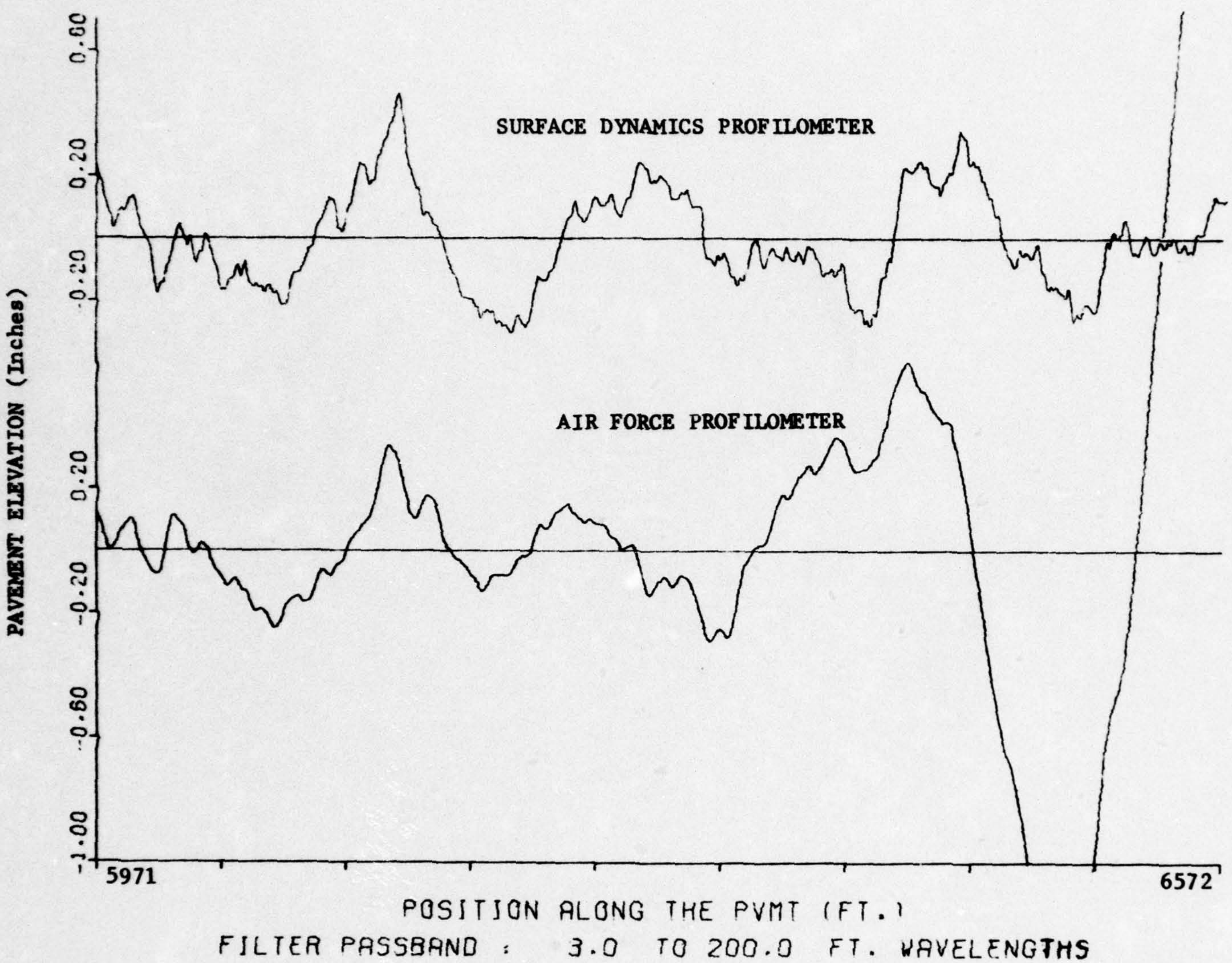


Fig A2.11c. Runway 35 Right, Centerline, Section C, File 1.

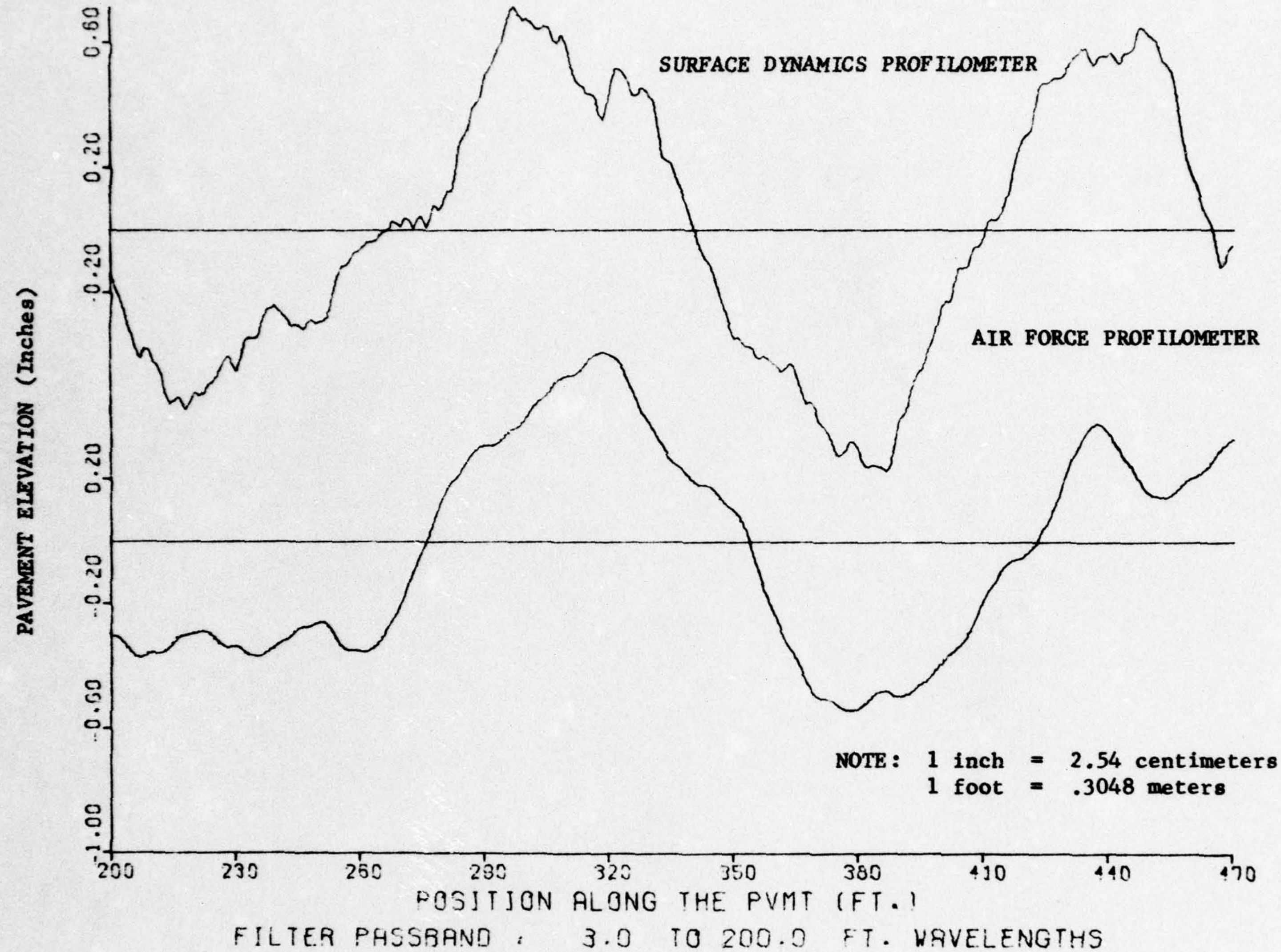


Fig A2.12a. Austin Test Section Number 3, Right Wheelpath, File 1.

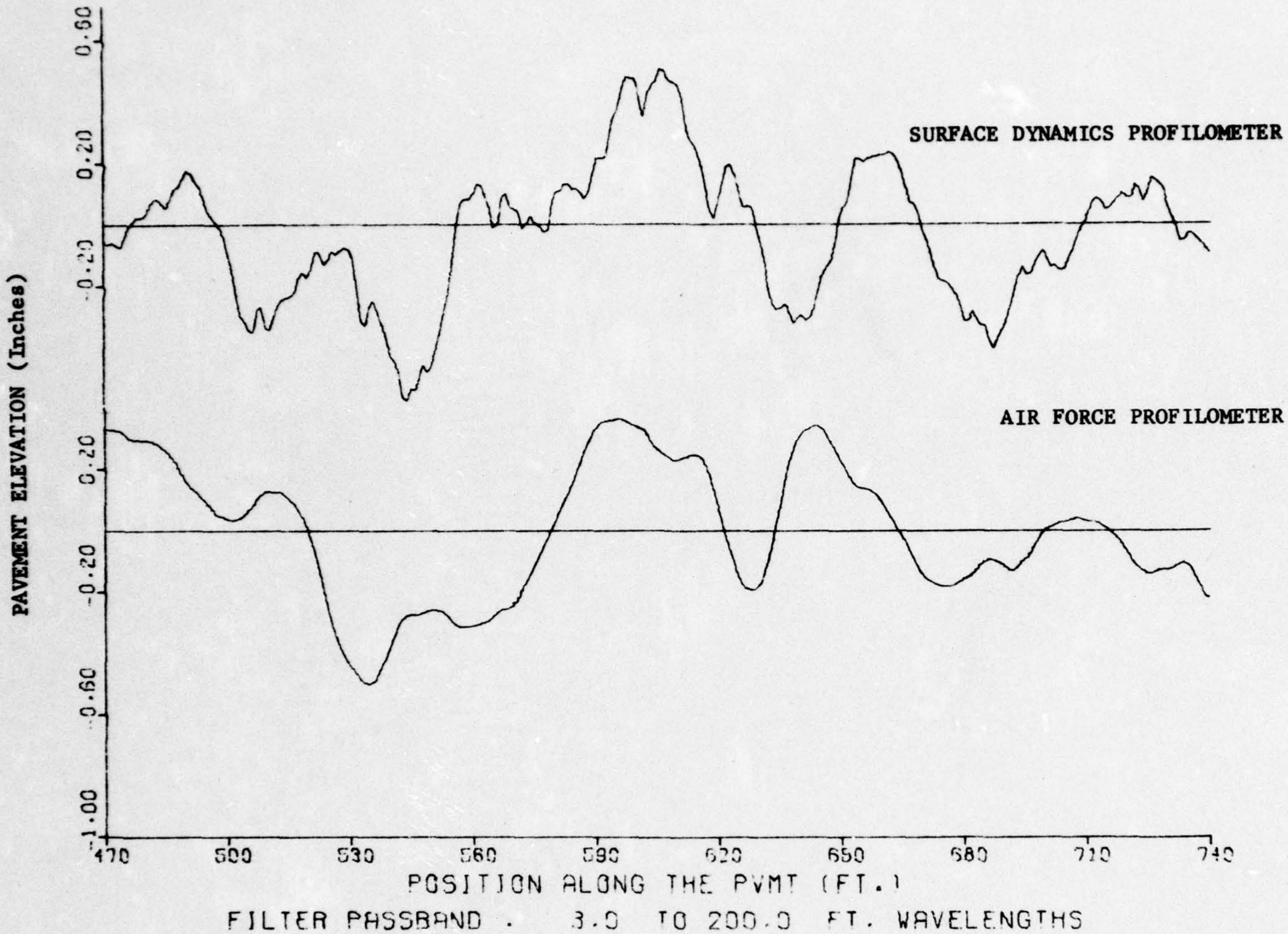


Fig A2.12b. Austin Test Section Number 3, Right Wheelpath, File 1.

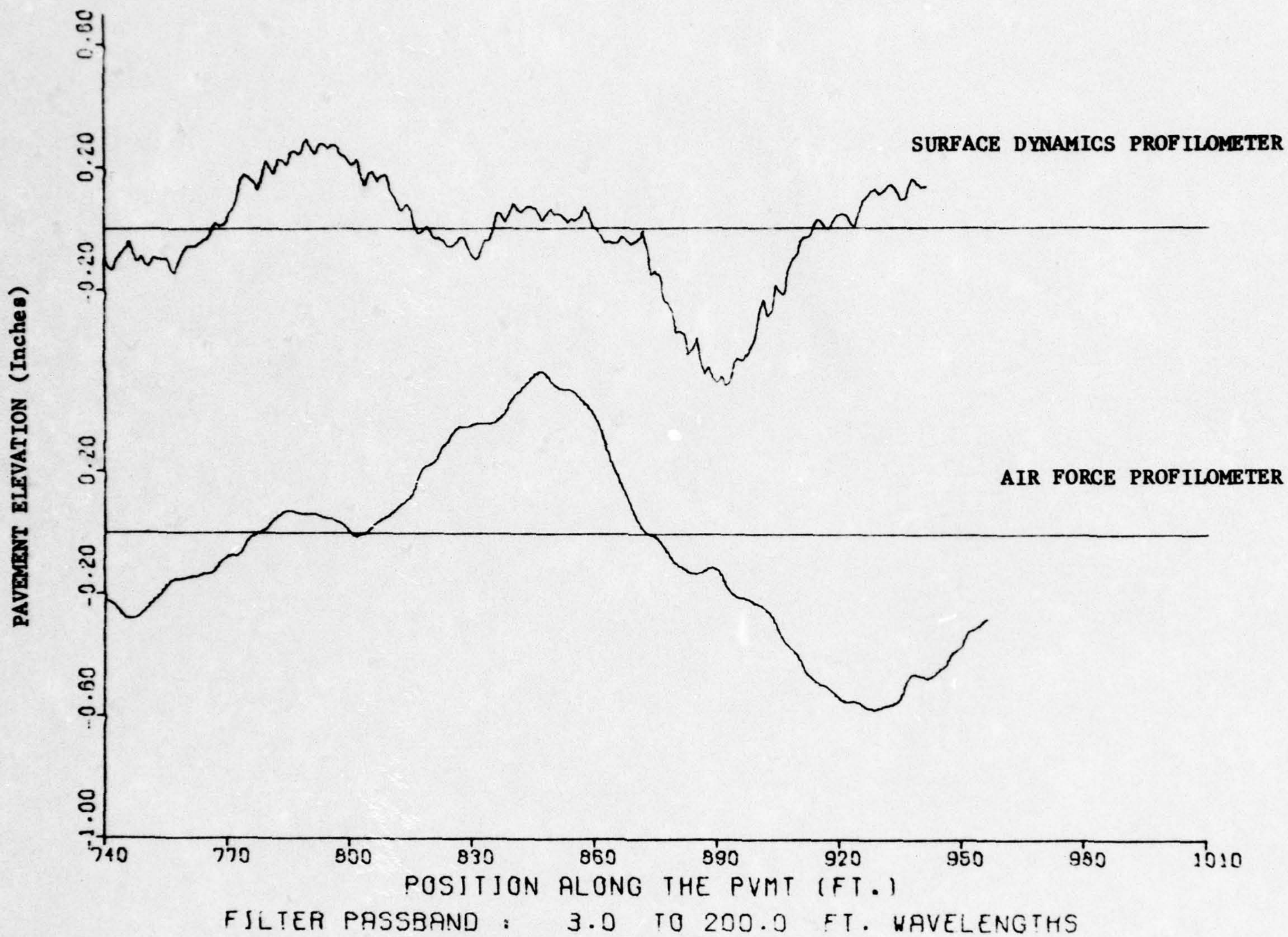


Fig A2.12c. Austin Test Section Number 3, Right Wheelpath, File 1.

APPENDIX 3

ROUGHNESS AMPLITUDE DATA
AND ANOVA RESULTS

TABLE A3.1. ROUGHNESS AMPLITUDES, RUNWAY 17 RIGHT, CENTERLINE

Pass-band (feet)	Vehicle	File	Section A Mean	Section A Standard Deviation	Section B Mean	Section B Standard Deviation	Section C Mean	Section C Standard Deviation	Section D Mean	Section D Standard Deviation
4 to 10	SD	1	.01042	.00425	.00925	.00398	.00937	.00395	NOT AVAILABLE	
		2	.01047	.00415	.00905	.00394	.00913	.00371		
	AF	1	.01221	.00534	.01073	.00460	.01031	.00538	NOT AVAILABLE	
		2	.01194	.00509	.01408	.03699	.01051	.00745		
		3	.01213	.00517	.01086	.00448	.01858*	.09749		
10 to 25	SD	1	.01828	.00615	.01737	.00796	.01735	.00644	NOT AVAILABLE	
		2	.01848	.00626	.01777	.00799	.01750	.00647		
	AF	1	.01966	.00700	.02008	.00679	.01850	.00739	NOT AVAILABLE	
		2	.02161	.00975	.02296	.03833	.01861	.00773		
		3	.01956	.00702	.01981	.00713	.04024*	.14968		
25 to 50	SD	1	.02896	.01027	.02532	.00856	.03117	.01231	NOT AVAILABLE	
		2	.02919	.01001	.02511	.00833	.03094	.01277		
	AF	1	.02482	.00754	.02197	.00627	.02937	.01180	NOT AVAILABLE	
		2	.02756	.01751	.02827	.03801	.02999	.01197		
		3	.02436	.00758	.02206	.00715	.06705*	.18213		
50 to 100	SD	1	.04529	.02712	.03688	.01224	.04501	.02661	NOT AVAILABLE	
		2	.04461	.02645	.03692	.01166	.04522	.02629		
	AF	1	.04102	.02755	.03264	.01185	.03987	.02397	NOT AVAILABLE	
		2	.04497	.03884	.04272	.04432	.03937	.02366		
		3	.03944	.02689	.03252	.01178	.11699*	.24988		

(Continued)

TABLE A3.1. (Continued)

Pass band (feet)	Vehicle	File	Section A Mean	Section A Standard Deviation	Section B Mean	Section B Standard Deviation	Section C Mean	Section C Standard Deviation	Section D Mean	Section D Standard Deviation
100 to 200	SD	1	.10172	.08180	.04999	.01989	.07325	.04369	NOT AVAILABLE	
		2	.10400	.08322	.04813	.02093	.07088	.03979		
	AF	1	.10040	.08504	.04670	.02273	.07443	.04263	NOT AVAILABLE	
		2	.11244	.09354	.06099	.06126	.06758	.03253		
		3	.10001	.08250	.05276	.03086	.24002*	.33420		
200 to 400	SD	1	.16272	.07966	.09665	.03020	.07272	.02766	NOT AVAILABLE	
		2	.15006	.09454	.07661	.03075	.05676	.03337		
	AF	1	.29177	.20570	.51439	.29792	1.50518	.66367	NOT AVAILABLE	
		2	.17193	.13832	.35621	.14733	.67744	.40004		
		3	.28873	.17680	.69611	.65002	1.58188*	1.18055		
3 to 200	SD	1	.12901	.08563	.08084	.01966	.10736	.04751	NOT AVAILABLE	
		2	.13025	.08659	.08002	.01966	.10482	.04537		
	AF	1	.12584	.08954	.08440	.03246	.11683	.05433	NOT AVAILABLE	
		2	.13705	.09881	.09320	.06783	.10909	.04978		
		3	.12811	.08816	.09367	.05311	.35311*	.53045		

*Eliminated Data

All values are in inches
NOTE: 1 inch = 2.54 centimeters
1 foot = .3048 meters

TABLE A3.2. ROUGHNESS AMPLITUDES, RUNWAY 17 RIGHT, RIGHT-OF-CENTER

Pass-band (feet)	Vehicle	File	Section A Mean	Section A Standard Deviation	Section B Mean	Section B Standard Deviation	Section C Mean	Section C Standard Deviation	Section D Mean	Section D Standard Deviation
4 to 10	SD	1	.01172	.00478	.01190	.00529	.01142	.00508	.01327	.00545
		2	.01238	.00536	.01198	.00532	.01189	.00512	.01322	.00550
	AF	1	.01108	.00456	.01133	.00526	.00999	.00438	.01137	.00467
		2	.01118	.00476	.01124	.00503	.00856	.00347	NOT AVAILABLE	
		3	.01163	.00478	.69035*	3.80368	.61449*	5.97174	.01144	.00449
10 to 25	SD	1	.02307	.00896	.02271	.00920	.02074	.00866	.02381	.00937
		2	.02411	.01014	.02250	.00906	.02165	.00897	.02405	.00938
	AF	1	.02333	.00864	.02338	.00918	.01985	.00786	.02099	.00861
		2	.02367	.01007	.02298	.00945	.01849	.00732	NOT AVAILABLE	
		3	.02320	.00946	1.57739*	6.05947	1.18502*	8.13838	.02091	.00851
25 to 50	SD	1	.03157	.01152	.02424	.00939	.03403	.01524	.02940	.01142
		2	.03371	.00935	.02671	.01082	.03551	.01519	.02948	.01100
	AF	1	.02896	.01078	.02259	.00771	.03125	.01390	.02676	.01100
		2	.03048	.00936	.02311	.00812	.03005	.01416	NOT AVAILABLE	
		3	.02964	.00986	1.71384*	4.56499	1.12948*	5.09612	.02672	.01171
50 to 100	SD	1	.04405	.02600	.03653	.01843	.04946	.03187	.05409	.02194
		2	.04535	.02715	.03800	.01701	.04845	.03209	.05670	.02218
	AF	1	.03998	.02379	.03443	.01653	.04354	.02896	.04830	.01951
		2	.04110	.02471	.03430	.01546	.04401	.02707	NOT AVAILABLE	
		3	.04027	.02482	1.75827*	3.24743	1.16720*	3.60737	.04835	.01928

(Continued)

TABLE A3.2. (Continued)

Pass-band (feet)	Vehicle	File	Section A Mean	Section A Standard Deviation	Section B Mean	Section B Standard Deviation	Section C Mean	Section C Standard Deviation	Section D Mean	Section D Standard Deviation
100 to 200	SD	1	.10888	.11765	.05831	.02146	.06172	.02543	.09937	.05622
		2	.11169	.12219	.06081	.01866	.06237	.02903	.09567	.05050
	AF	1	.10219	.10670	.05655	.02110	.06037	.02328	.11830	.07307
		2	.10103	.10904	.05814	.02479	.07065	.03834	NOT AVAILABLE	
		3	.10213	.10715	1.60964*	2.08225	1.24820*	2.50023	.12800	.09247
200 to 400	SD	1	.15966	.10732	.08919	.03752	.06898	.03247	.12346	.04164
		2	.16530	.11141	.07597	.02739	.06187	.03492	.11452	.03562
	AF	1	.20900	.12734	.54850	.38175	1.19210	.57086	3.27139	1.02956
		2	.31175	.19424	.67424	.62643	1.39110	1.22633	NOT AVAILABLE	
		3	.22555	.16296	1.81417*	1.36769	2.08626*	1.36422	3.01662	1.48535
3 to 200	SD	1	.14092	.11609	.09037	.02126	.10357	.03704	.13719	.05397
		2	.14528	.12118	.09379	.01987	.10452	.03964	.13538	.04795
	AF	1	.13159	.10484	.08686	.01866	.09517	.03013	.14267	.04925
		2	.13215	.10751	.08800	.02111	.10375	.03942	NOT AVAILABLE	
		3	.13171	.10645	6.19566*	9.66221	4.72859*	13.53004	.15623	.08664

*Eliminated Data

All values are in inches

NOTE: 1 inch = 2.54 centimeters
1 foot = .3048 meters

TABLE A3.3. ROUGHNESS AMPLITUDES, RUNWAY 17 RIGHT, LEFT-OF-CENTER

Pass-band (feet)	Vehicle	File	Section A Mean	Section A Standard Deviation	Section B Mean	Section B Standard Deviation	Section C Mean	Section C Standard Deviation	Section D Mean	Section D Standard Deviation
4 to 10	SD	1	.01438	.00629	.01139	.00484	.00964	.00402	.01018	.00485
		2	.01262	.00536	.01159	.00475	.00981	.00378	.01100	.00897
	AF	1	.01305	.00546	.01115	.00462	.00858	.00386	.00957	.00482
		2	.01270	.00625	.01129	.00416	.00843	.00368	.00954	.00558
		3	.01352	.00611	.35395*	3.38556	.00892	.00416	.00973	.00581
25 to 50	SD	1	.02208	.00648	.02035	.00742	.01998	.00740	.02031	.00965
		2	.02262	.00654	.01984	.00776	.01964	.00726	.02019	.01036
	AF	1	.02253	.00774	.02112	.00731	.01955	.00704	.02005	.00938
		2	.02121	.00883	.02154	.00736	.01886	.00737	.01977	.00883
		3	.02194	.00649	.68112*	4.61227	.01980	.00712	.02053	.00894
25 to 50	SD	1	.03504	.01413	.02613	.01129	.02956	.01406	.03284	.01181
		2	.03620	.01526	.02616	.01091	.02911	.01353	.03163	.01253
	AF	1	.03113	.01451	.02331	.00836	.02697	.01206	.02837	.01136
		2	.02918	.01217	.02348	.00911	.02741	.01223	.02770	.01294
		3	.03087	.01340	.64471*	2.88741	.02699	.01179	.02819	.01033
50 to 100	SD	1	.04973	.02758	.04669	.01341	.04835	.02288	.04073	.01470
		2	.04782	.02910	.04691	.01359	.04798	.02110	.04230	.01490
	AF	1	.04462	.02302	.04181	.01164	.04575	.02374	.03599	.01335
		2	.04478	.02340	.04140	.01107	.04395	.02289	.03814	.01367
		3	.04496	.02614	.68354*	2.04803	.04577	.02211	.03679	.01317

(Continued)

TABLE A3.3. (Continued)

Pass-band (feet)	Vehicle	File	Section A Mean	Section A Standard Deviation	Section B Mean	Section B Standard Deviation	Section C Mean	Section C Standard Deviation	Section D Mean	Section D Standard Deviation
100 to 200	SD	1	.07405	.05553	.05217	.01878	.08258	.05215	.10858	.04663
		2	.07530	.05659	.05037	.01931	.07700	.04720	.11139	.04767
	AF	1	.07248	.05526	.05265	.02601	.08452	.04552	.12919	.07351
		2	.07371	.06155	.04918	.01660	.07419	.04153	.11055	.05235
		3	.06746	.05446	.72388*	1.39799	.09706	.06225	.14161	.10430
200 to 400	SD	1	.10960	.03050	.09285	.03110	.08929	.03881	.13168	.03188
		2	.10239	.02827	.07930	.03116	.08006	.02060	.13356	.04336
	AF	1	.24386	.15116	.63287	.29667	1.47297	.63194	3.57702	.67729
		2	.14596	.06906	.29995	.17182	.74722	.62173	1.37562	.77633
		3	.43624	.37022	1.66509*	.79453	2.40259	1.58444	2.40669	1.21213
3 to 200	SD	1	.11470	.05789	.09061	.01497	.11788	.05141	.13453	.04800
		2	.11602	.05847	.08961	.01484	.11252	.04705	.13705	.05101
	AF	1	.10872	.05508	.08505	.02013	.11188	.04377	.14159	.04843
		2	.10834	.06181	.08278	.01419	.10538	.04472	.13439	.05192
		3	.10481	.05631	2.70936*	7.66133	.12796	.05674	.16141	.10115

*Eliminated Data

All values are in inches

NOTE: 1 inch = 2.54 centimeters
1 foot = .3048 meters

TABLE A3.4. ROUGHNESS AMPLITUDES (inches), FLEXIBLE PAVEMENT

Pass-band (feet)	Vehicle	File	Runway 35 Right Centerline						Austin Test Section Number 3	
			Section A		Section B		Section C			
			Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
4 to 10	SD	1	.01148	.00669	.01217	.00779	.01430	.01239	.01641	.00668
		2	.01200	.00701	.01236	.00726	.01350	.01202	.01670	.00700
	AF	1	.00477	.00683	.00349	.00161	.00382	.00189	.00381	.00153
		2	.00369	.00150	.00370	.00152	.00425	.00201	.00377	.00187
10 to 25	SD	1	.01995	.00990	.02167	.01176	.02912	.01932	.02293	.01108
		2	.02042	.01007	.02168	.01193	.02944	.01894	.02236	.01089
	AF	1	.01503	.00975	.01388	.00940	.02358	.01467	.01398	.00811
		2	.01392	.00646	.01321	.00904	.02339	.01488	.01849	.00714
25 to 50	SD	1	.03866	.01705	.03513	.02269	.04298	.02760	.06125	.03519
		2	.03707	.01536	.03460	.02118	.04248	.02678	.06180	.03488
	AF	1	.02664	.01225	.02398	.01405	.04049	.02860	.04605	.02369
		2	.02613	.01149	.02322	.01398	.04014	.02725	.04709	.02116
50 to 100	SD	1	.09243	.03447	.07797	.03623	.07165	.05183	.09289	.03118
		2	.09142	.03311	.07860	.03595	.07405	.04930	.09747	.03463
	AF	1	.08837	.03163	.06322	.03774	.06090	.03950	.06922	.02401
		2	.08671	.02961	.06536	.03665	.06146	.04052	.07640	.02531
100 to 200	SD	1	.20574	.06240	.13733	.05968	.15627	.05152	.23397	.11879
		2	.20542	.05769	.14156	.05698	.15588	.05449	.22191	.12097
	AF	1	.17098	.03754	.12934	.03546	.15845	.07473	.22982	.07290
		2	.18099	.04396	.12637	.03567	.15207	.06741	.19267	.09689

(Continued)

TABLE A3.4. (Continued)

Pass-band (feet)	Vehicle	File	Runway 35 Right Centerline						Austin Test Section Number 3	
			Section A		Section B		Section C			
			Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
200 to 400	SD	1	.28019	.08069	.18660	.06202	.28868	.15255	Not Accomplished	
		2	.28280	.08233	.17804	.06764	.30647	.14319		
	AF	1	.43160	.30537	.14460	.63350	3.15562	1.00949		
		2	.39367	.26699	.99453	.58214	3.29342	.68001		
3 to 200	SD	1	.24838	.06315	.18866	.05522	.20173	.06961	.28825	.10310
		2	.24773	.05832	.19134	.05295	.20231	.07226	.28221	.10159
	AF	1	.21084	.04162	.18916	.08720	.23539	.14436	.26025	.06204
		2	.21684	.04677	.18397	.07616	.22574	.13319	.23243	.08451

All values are in inches

NOTE: 1 inch = 2.54 centimeters
1 foot = .3048 meters

TABLE A3.5a. ANALYSIS OF VARIANCE, RIGID PAVEMENT, 4 to 10 FOOT WAVELENGTHS

Source of Variance	Sum of Squares × 10^6	Degrees of Freedom	Mean Square × 10^6	F Ratio
Profilometer Main Effects	.7943	1	.7943	1.98
Section Main Effects	64.1257	10	6.4126	15.95
Interactions	26.0507	10	2.6051	6.48*
Error	11.2592	28	.4021	

*Significant at α = .025 level

TABLE A3.5b. CELL MEANS, RIGID PAVEMENT, 4 to 10 FOOT WAVELENGTHS

Section	Surface Dynamics	Air Force	Percent Difference (SD-AF)/AF
1 (CL-A)	.01045	.01209	-13.56
2 (CL-B)	.00915	.01189	-23.04
3 (CL-C)	.00925	.01041	-11.14
4 (ROC-A)	.01205	.01130	6.64
5 (ROC-B)	.01194	.01129	5.76
6 (ROC-C)	.01166	.00928	25.65
7 (ROC-D)	.01325	.01141	16.13
8 (LOC-A)	.01350	.01309	3.13
9 (LOC-B)	.01149	.01122	2.41
10 (LOC-C)	.00973	.00864	12.62
11 (LOC-D)	.01059	.00961	10.20
TOTAL	.01119	.01093	2.32

TABLE A3.6a. ANALYSIS OF VARIANCE, RIGID PAVEMENT, 10 to 25 FOOT WAVELENGTHS

Source of Variance	Sum of Squares $\times 10^6$	Degrees of Freedom	Mean Square $\times 10^6$	F Ratio
Profilometer Main Effects	.4101	1	.4101	.88
Section Main Effects	134.9166	10	13.4917	28.86
Interactions	33.9907	10	3.3991	7.27*
Error	13.0901	28	.4675	

*Significant at α = .025 level

TABLE A3.6b. CELL MEANS, RIGID PAVEMENT, 10 TO 25 FOOT WAVELENGTHS

Section	Surface Dynamics	Air Force	Percent Difference (SD-AF)/AF
1 (CL-A)	.01838	.02028	- 9.37
2 (CL-B)	.01757	.02095	-16.13
3 (CL-C)	.01743	.01856	- 6.09
4 (ROC-A)	.02359	.02340	0.81
5 (ROC-B)	.02261	.02318	- 2.46
6 (ROC-C)	.02120	.01917	10.59
7 (ROC-D)	.02393	.02095	14.22
8 (LOC-A)	.02235	.02189	2.10
9 (LOC-B)	.02010	.02133	- 5.77
10 (LOC-C)	.01981	.01940	2.11
11 (LOC-D)	.02025	.02012	0.65
TOTAL	.02066	.02084	- 0.86

TABLE A3.7a. ANALYSIS OF VARIANCE, RIGID PAVEMENT, 25 to 50 FOOT WAVELENGTHS

Source of Variance	Sum of Squares $\times 10^6$	Degrees of Freedom	Mean Square $\times 10^6$	F Ratio
Profilometer Main Effects	107.0162	1	107.0162	66.70
Section Main Effects	437.9781	10	43.7978	27.30
Interactions	17.0270	10	1.7027	1.06
Error	44.9221	28	1.6044	

TABLE A3.7b. CELL MEANS, RIGID PAVEMENT, 25 TO 50 FOOT WAVELENGTHS

Section	Surface Dynamics	Air Force	Percent Difference (SD-AF)/AF
1 (CL-A)	.02908	.02558	13.68
2 (CL-B)	.02522	.02410	4.65
3 (CL-C)	.03106	.02968	4.65
4 (ROC-A)	.03264	.02969	9.94
5 (ROC-B)	.02548	.02285	11.51
6 (ROC-C)	.03477	.03065	13.44
7 (ROC-D)	.02944	.02674	10.10
8 (LOC-A)	.03562	.03039	17.21
9 (LOC-B)	.02615	.02340	11.75
10 (LOC-C)	.02934	.02712	8.19
11 (LOC-D)	.03224	.02809	14.77
TOTAL	.03009	.02712	10.95

TABLE A3.8a. ANALYSIS OF VARIANCE, RIGID PAVEMENT, 50 to 100 FOOT WAVELENGTHS

Source of Variance	Sum of Squares $\times 10^6$	Degrees of Freedom	Mean Square $\times 10^6$	F Ratio
Profilometer Main Effects	208.9252	1	208.9252	58.71
Section Main Effects	981.1380	10	98.1138	27.57
Interactions	29.3578	10	2.9358	.83
Error	99.6338	28	3.5583	

TABLE A3.8b. CELL MEANS, RIGID PAVEMENT, 50 TO 100 FOOT WAVELENGTHS

Section	Surface Dynamics	Air Force	Percent Difference (SD-AF)/AF
1 (CL-A)	.04495	.04181	7.51
2 (CL-B)	.03690	.03596	2.61
3 (CL-C)	.04512	.03962	13.88
4 (ROC-A)	.04470	.04045	10.51
5 (ROC-B)	.03727	.03437	8.44
6 (ROC-C)	.04896	.04378	11.83
7 (ROC-D)	.05540	.04833	14.63
8 (LOC-A)	.04878	.04479	8.91
9 (LOC-B)	.04680	.04161	12.47
10 (LOC-C)	.04817	.04516	6.67
11 (LOC-D)	.04152	.03697	12.31
TOTAL	.04532	.04117	10.08

TABLE A3.9a. ANALYSIS OF VARIANCE, RIGID PAVEMENT, 100 to 200 FOOT WAVELENGTHS

Source of Variance	Sum of Squares × 10^6	Degrees of Freedom	Mean Square × 10^6	F Ratio
Profilometer Main Effects	175.9243	1	175.9243	4.28
Section Main Effects	27358.0436	10	2735.8044	66.59
Interaction	1022.0838	10	102.2084	2.49 *
Error	1150.4119	28	41.0861	

*Significant at α = .05 level

TABLE A3.9b. CELL MEANS, RIGID PAVEMENT, 100 TO 200 FOOT WAVELENGTHS

Section	Surface Dynamics	Air Force	Percent Difference (SD-AF)/AF
1 (CL-A)	.10286	.10428	- 1.36
2 (CL-B)	.04906	.05348	- 8.26
3 (CL-C)	.07207	.07101	1.49
4 (ROC-A)	.11029	.10178	8.36
5 (ROC-B)	.05956	.05735	3.85
6 (ROC-C)	.06205	.06551	- 5.28
7 (ROC-D)	.09752	.12315	-20.81
8 (LOC-A)	.07468	.07122	4.86
9 (LOC-B)	.05127	.05092	0.69
10 (LOC-C)	.07979	.08526	- 6.42
11 (LOC-D)	.10999	.12711	-13.47
TOTAL	.07901	.08282	- 4.60

TABLE 3.10a. ANALYSIS OF VARIANCE, RIGID PAVEMENT, 200 to 400 FOOT WAVELENGTHS

Source of Variance	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Profilometer Main Effects	11.5547	1	11.5547	73.88
Section Main Effects	10.1912	10	1.0191	6.52
Interactions	10.2732	10	1.0273	6.57*
Error	4.3792	28	.1564	

*Significant at α = .025 level

TABLE 3.10b. CELL MEANS, RIGID PAVEMENT, 200 TO 400 FOOT WAVELENGTHS

Section	Surface Dynamics	Air Force	Percent Difference (SD-AF)/AF
1 (CL-A)	.15639	.25081	-37.65
2 (CL-B)	.08663	.52224	-83.41
3 (CL-C)	.06474	1.09131	-94.07
4 (ROC-A)	.16248	.24877	-34.69
5 (ROC-B)	.08258	.61137	-86.49
6 (ROC-C)	.06543	1.29160	-94.93
7 (ROC-D)	.11899	3.14401	-96.22
8 (LOC-A)	.10600	.27535	-61.50
9 (LOC-B)	.08608	.46641	-81.54
10 (LOC-C)	.08468	1.54093	-94.50
11 (LOC-D)	.13262	2.45311	-94.59
TOTAL	.10424	1.08145	-90.36

TABLE A3.11a. ANALYSIS OF VARIANCE, RIGID PAVEMENT, 3 to 200 FOOT WAVELENGTHS

Source of Variance	Sum of Squares $\times 10^6$	Degrees of Freedom	Mean Square $\times 10^6$	F Ratio
Profilometer Main Effects	3.3969	1	3.3969	.10
Section Main Effects	20544.7421	10	2054.4742	57.60
Interaction	770.0530	10	77.0053	2.16*
Error	998.6677	28	35.6667	

*Significant at α = .10 level

TABLE A3.11b. CELL MEANS, RIGID PAVEMENT, 3 TO 200 FOOT WAVELENGTHS

Section	Surface Dynamics	Air Force	Percent Difference (SD-AF)/AF
1 (CL-A)	.12963	.13033	- 0.54
2 (CL-B)	.08043	.09042	-11.05
3 (CL-C)	.10609	.11296	- 6.08
4 (ROC-A)	.14310	.13182	8.56
5 (ROC-B)	.09208	.08743	5.32
6 (ROC-C)	.10405	.09946	4.61
7 (ROC-D)	.13629	.14945	-8.81
8 (LOC-A)	.11536	.10729	7.52
9 (LOC-B)	.09011	.08392	7.38
10 (LOC-C)	.11520	.11507	0.11
11 (LOC-D)	.13579	.14580	6.87
TOTAL	.11347	.11400	- 0.46

APPENDIX 4

AN INVESTIGATION INTO THE APPLICATION OF THE SERVICEABILITY-PERFORMANCE CONCEPT TO AIRFIELD PAVEMENT DESIGN

APPENDIX 4. AN INVESTIGATION INTO THE APPLICATION OF THE PAVEMENT SERVICEABILITY-PERFORMANCE CONCEPT TO AIRFIELD PAVEMENT DESIGN

INTRODUCTION

The introduction of the pavement serviceability-performance concept, as presented by Carey and Irick (Ref 1), has been one of the most important developments in the field of highway pavement design. Considerable progress has been made in developing a systems approach to highway pavement design by utilizing this concept as the basis for determining the performance of a pavement. Although work has been done in conceptualizing a similar systems approach to airfield pavement design (Refs 3 and 4), relatively little has been accomplished in applying the serviceability-performance concept to the more complex realm of airfield pavement design.

In order to further the development of the airfield pavement system as proposed by Hudson and Kennedy (Ref 3), some method of measuring airfield pavement performance is required. A serviceability-performance technique, similar to that used for highway pavements, could resolve this deficiency, and thereby allow better design and maintence of airfield pavements.

BACKGROUND

In order to develop a serviceability-performance technique for evaluating airfield pavements, one must first be familar with the technique as it applies to the evaluation of highway pavements. The basic assumptions of the highway technique are that " . . . the quality of service provided by the pavement is subjective on the whole, and the serviceability of a given pavement is defined as the mean of the subjective ratings given to it by all of its users," (Ref 6). A history of serviceability ratings can then be used as an indication of the performance of a particular highway pavement section. Carey and Irick (Ref 1) also demonstrated that serviceability

values also could be obtained from objective measurements of certain pavement characteristics (e.g., slope variance, amounts of cracking and patching, and rutting). More recent developments have enabled the determination of estimates of serviceability ratings from power spectral density analysis (Ref 22) and digital filtering (Ref 19) of pavement profiles obtained with the Surface Dynamics Profilometer.

There exist, then, two approaches for determining the serviceability and thus the performance of a particular pavement section:

(1) subjective ratings given to the pavement by all of its users and

(2) estimates or predictions of subjective ratings derived from objective measurements of pavement characteristics.

McCullough and Steitle (Ref 6) developed a subjective rating procedure for airfield runways as part of a study to establish guidelines for roughness evaluation. This is, however, the only known example of subjective ratings (as given by airline pilots) given to airfield pavements. Quite the opposite is true concerning efforts involving objective measurements of airfield pavements. The National Aeronautics and Space Administration (NASA), the U.S. Air Force, the Federal Aviation Administration (FAA), and others, are currently or have been conducting research on airfield pavement evaluation.

The primary course of the work done by the above agencies involves the development of criteria to define the characteristics of runway roughness that would indicate runway failure. The early efforts to characterize runway roughness utilized power spectral curves to define acceptable and unacceptable levels of roughness. It was soon discovered, however, that " . . . the power spectral criterion was not completely satisfactory to define an acceptable level of roughness for all operating problems," primarily because of its inability to distinguish between a large amount of small amplitude roughness and a small amount of large amplitude roughness (Ref 20).

More recent efforts in runway roughness research utilize aircraft response as measures of roughness. Various aircraft responses, such as landing gear stress, center-of-gravity and cockpit normal accelerations, pitch, and roll, are obtained by instrumenting aircraft or through computerized aircraft response simulations. In general, the normal acceleration responses have been used to evaluate human failure (user response to roughness), while others are more related to component and structural failure.

The criterion for separating satisfactory and unsatisfactory runways, as concerns human response, has been suggested as maximum vertical accelerations in the cockpit not exceeding ± 0.4g (Ref 20). This criterion has tended to be supported by pilot observations of runway roughness (Refs 5, 23, and 24), where pilot comparisons of roughness on several runways agreed qualitatively with the comparisons of cockpit accelerations.

Although the ± 0.4g criterion has been shown to relate to user (pilot) response, a subjective rating technique of some form, such as in Reference 6, has yet to be utilized on a large enough scale to relate such subjective indications of serviceability or performance to objective measurements. It is believed that major progress could be made in defining airfield pavement failure by establishing an airfield serviceability rating system and by gathering sufficient data to relate such ratings to objective measurements of airfield pavements.

FORMULATION OF AN AIRFIELD SERVICEABILITY-PERFORMANCE CONCEPT

Following a minimum program for the establishment, derivation, and validation of a Present Serviceability Index as presented by Carey and Irick (Ref 1), the following section applies to the establishment, derivation, and validation of a similar index for airfield pavements.

Establishment of Definitions

To establish uniformity, a precise understanding of terms is necessary for all involved in this process. The following definitions are proposed for an airfield pavement serviceability-performance concept and differ only slightly from those given by Carey and Irick:

Present Serviceability - the ability of a specific section of pavement to serve high-speed, high volume, mixed (heavy and light aircraft) traffic in its existing condition.

Individual Airfield Serviceability Rating - an independent rating by an individual of the present serviceability of a specific section of runway or taxiway made by marking the appropriate point on a rating scale.

Airfield Serviceability Rating (ASR) - the mean of the individual ratings made by the members of a specific rating panel.

Airfield Serviceability Index (ASI) - a mathematical combination of values obtained from certain physical measurements of a large number of airfield pavements so formulated as to predict the ASR for those pavements within prescribed limits.

Airfield Performance Index (API) - a summary of ASI values over a period of time.

These definitions are essentially the same as those defined by Carey and Irick with only certain words or wording changed to make certain it is understood that they apply to airfield pavements. This is necessary, in part, due to the work already done by McCullough and Steitle (Ref 6), where the rating scale is opposite that of the highway rating scale (i.e., the range of 0 to 1 is "very good" instead of "very poor"). It remains undecided whether this reversal of scale, based on an assumption that pilots would be rating the amount of roughness encountered rather than the lack of it (Ref 6), should be retained. If the scale were not reversed, the terms ASR, ASI, and API could remain as PSR, PSI, and PI, but they would apply to both highway and airfield pavements.

Establishment of Rating Group or Panel

To be a true indication of how an airfield pavement is serving traffic, individual ASR's should be given by a representation of all users. This however, is not practical, and research (Refs 23, 24) has shown that the aircraft pilot experiences greater accelerations than to the passengers. In addition, it is the pilot who is responsible for the safety and comfort of the passengers. It is therefore reasonable to conclude that using pilots, and possibly other crew members in the cockpit, as rating panel members would provide satisfactory user ratings. Also, it should be recognized that many aircraft have no passenger carrying capability and thus a requirement for passenger ratings would not apply to many aircraft types and the pavements they use.

Orienting and Training of the Rating Panel

Important in either the highway or airfield case, this step can also be one of the most difficult. If special panels were assembled to rate all pavement sections, training would be relatively simple. However, for a more practical and less expensive approach, adequate instructions and rating forms could be distributed to airline pilots who frequently operate at the airfield to be rated, as was done in Reference 6. This step would be relatively easy for military airfields as a majority of traffic is regularly scheduled and usually returns within a short period of time.

Selection of Pavements for Rating

A wide range of pavement types, locations, and conditions should be included. The selection process can be expensive, as a large number of airfields will have to be studied, and, to be representative, will have to be geographically separated by large distances. It is quite possible that selection of pavements could be dictated by the ability to obtain the physical measurements necessary to derive an ASI.

The steps of field rating, replication, and validation require no special emphasis over that of the highway application. Standard experimental procedures apply in both cases.

Physical Measurements

There are two basic categories of surface characteristics that can be described by measurements: deformation and deterioration. The PSI equation derived by Carey and Irick included both types; slope variance and rut depth representing surface deformation, and cracking and patching representing surface deterioration. Presently available PSI models (Ref 19) have been developed on the basis that "serviceability was a function primarily of longitudinal and transverse profile . . ." (Ref 1). Profile measurements for these models are being made with the Surface Dynamics Profilometer. It is thus anticipated that the optimum measurements to obtain for airfield pavements would also be profiles obtained from relatively high speed profilometers such as the Surface Dynamics Profilometer or the U.S. Air Force owned profilometer systems. As there are three wheelpaths for

almost all aircraft, profiles should be taken along three lines: left-of-centerline, centerline, and right-of-centerline; lateral separation of the left and right-of-centerline surveys can be established as an average for various aircraft landing gear spacings, as the actual lateral location of each aircraft operation is variable. It should hardly require noting that the physical measurements should be obtained at approximately the same time as the rating sessions are conducted because the pavement profiles will vary with time.

Summaries of Measurements

Numerous methods of summarizing profiles are available: slope and cross-slope variance, roughness index, power spectral density analysis, etc. Present summaries being utilized by the Center for Highway Research and the U. S. Air Force (Ref 25) are the mean square and root mean square amplitudes of digitally-filtered profiles. As these summaries provide straightforward indications of roughness, it is believed that they should be used in the derivation of an Airfield Serviceability Index.

Derivation of an Airfield Serviceability Index

The final step in the formulation of an airfield serviceability-performance concept is to develop a mathematical formula that will predict ASR's within a satisfactory tolerance. In addition to profile measurement variables, it is believed that other variables indicating certain aircraft characteristics must be included in the formula, resulting in a general mathematical form for the Airfield Serviceability Index of

$$ASI = K + \left(\sum_{i=1}^{n} A_i R_i\right) + \left(\sum_{j=1}^{m} B_j C_j\right)$$

where

R_i values are functions of the profile roughness; C_j values are functions of aircraft characteristics; and K , A_i , and B_j are coefficients

determined by multiple linear regression analysis. The inclusion of nonlinear terms, including interactions, should be considered. The regression analysis would be used also to determine which variables are the most important and those that could be neglected in the ASR predicting equation.

VARIABLES IN THE ASI EQUATION

The general form of the ASI equation presented above includes variables that are functions of the profile roughness and aircraft characteristics. As previously mentioned, it is believed that the most applicable measures of roughness are mean square and root mean square roughness amplitudes. However, as an aircraft is accelerating for take-off or decelerating when landing its velocity is constantly changing. Since an aircraft will respond differently to the same profile, depending on the aircraft velocity (Ref 6), the location of the types of roughness becomes an important factor (e.g., a long, rolling profile is not as critical at the start of a take-off, where velocity is low, as it is just prior to take-off, where velocity is high). As a result of the importance of roughness location, discrete segments of the profile should be analyzed, creating a matrix of roughness variables for the regression analysis.

There are many characteristics to consider when deciding which variables of aircraft characteristics to include in the regression analysis. Each aircraft and its operation are unique, as weights, gear spacings, configurations, etc. vary, thus providing different influences on the pilot and his rating of a runway. An example of these influences can be seen upon examining the individual ASR's given in Reference 6, where the riding quality generally decreased as aircraft size/weight increased. It is believed that the most significant variable of aircraft characteristics would be a function of the aircraft weight, as other characteristics are related to the aircraft weight. Once again, the regression analysis would indicate the importance of the selected variables.

The variation of the individual ASR's according to aircraft size, as given in Reference 6, complicates the derivation of ASI's. By definition, the ASR of a particular airfield pavement is the mean of individual ratings given by a panel representing all users. There are, however, airfields that

do not or cannot serve all users or all sizes of aircraft due to runway length and thickness, military mission, etc. This is not so great a problem in determining ASI's, as a set of ASI's could be determined (one for each aircraft type/size) and then combined to produce an overall ASI to represent all potential users. However, individual ASR's for each aircraft type/size at each airfield might not be available and this would prohibit the formulation of an ASR to represent all potential users. It is therefore suggested that the ASR and ASI values for each airfield represent only the actual or present users and not potential users. This would indicate that an identical serviceability for two airfields would not imply that the airfields could serve identical traffic in the same manner.

Overall ASR and ASI values of individual airfields, thus being unique to each airfield and its traffic, would be some weighted functions of sets of ASR and ASI values for individual aircraft types/sizes. It is unknown at this time, because of the limited amount of available data, whether significant differences would exist between the take-off and landing operations thus necessitating further subdivision of rating conditions. It is therefore possible that the following formulations would apply:

$$ASR = f\,(ASR_{1,TO},\ ASR_{1,L},\ \ldots\ ASR_{ij},\ \ldots)$$

where

ASR_{ij} represents and ASR for the i^{th} aircraft type and j^{th} operation (take-off or landing) ,

$$ASI = f\,(ASI_{1,TO},\ ASI_{1,L},\ \ldots\ ASI_{ij},\ \ldots)$$

where

ASI_{ij} has the same connotations as ASR_{ij} above.

CONCLUSIONS

The application of the serviceability-performance concept to airfield pavements is a complex matter, due in most part to the wide variability of the using aircraft. A pavement that serves one type of aircraft well will not necessarily give the same level of service to another type of aircraft. As such, the serviceability ratings and indices obtained and derived for an airfield should take into account the present using aircraft types, not all aircraft types. This is also consistent with the definition of Present Serviceability.

The preliminary work done by McCullough and Steitle (Ref 6) in developing a serviceability technique for airfield pavements tends to support the establishment of ASR and ASI values for groups of aircraft types and sizes. Overall ASR and ASI values for each pavement section (runway, taxiway, etc.) could be determined as weighted combinations of the aircraft type/size ASR and ASI values. One possible method for weighting these values would be according to the traffic distribution or mix on each pavement section.

The work necessary to obtain all the required data to implement the foregoing discussion is by no means simple. One or several rating panels must be established, trained, and then rate a sufficiently large sample of airfield pavements (138 pavement sections were rated for the highway case). Profile measurements must be taken for all of the pavement sections thus rated, and at approximately the time that the rating sessions occur. With such large amounts of information, much effort will have to be expended to derive an expression for ASI values. If considered as a separate effort, the cost and amount of time required to undertake the preliminary development of an airfield serviceability-performance concept could be prohibitive. As such, some consideration should be given to the establishment of rating sessions in conjuction with other ongoing research that obtains the required physical measurements.

This investigation into the application of the serviceability-performance concept to airfield pavements is by no means complete. Several decisions remain to be made and most likely will depend on the data gathering and regression analysis yet to be accomplished. Even though much time, effort,

and expenditure will be required to realize a serviceability technique for airfield pavements, the long-range impact and benefits of such work more than justify any efforts to further develop such concepts.

VITA

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